SOUND WAVES

THEIR SHAPE AND SPEED

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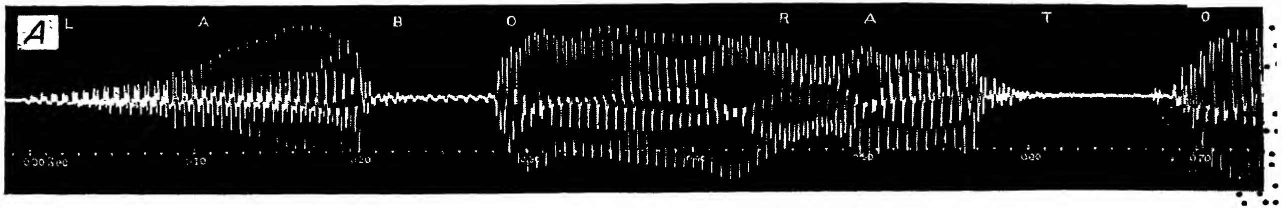
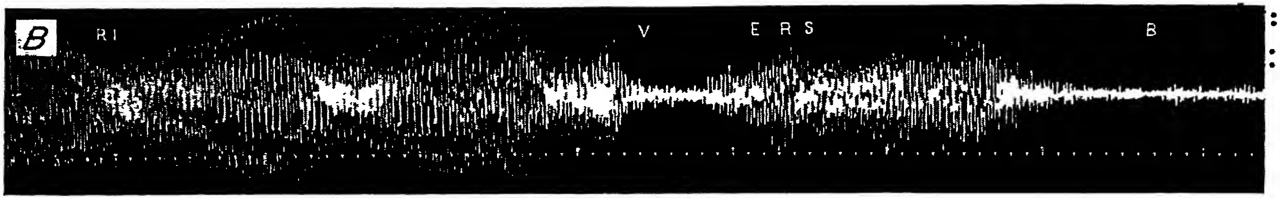
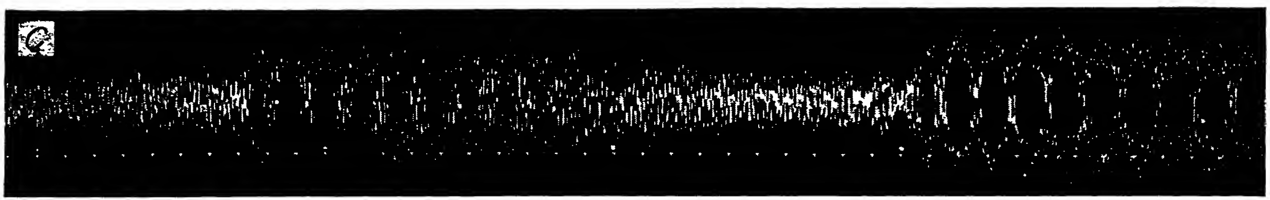
Photographs of Sounds Made with the Phonodeik.



The word "laboratory" spoken by D. C. M.



Music—Voice and Orchestra.



The clanging of a bell.

SOUND WAVES

THEIR SHAPE AND SPEED

A DESCRIPTION OF THE PHONODEIK AND ITS APPLICATIONS AND A REPORT ON A SERIES OF INVESTIGATIONS MADE AT SANDY HOOK PROVING GROUND

BY

DAYTON CLARENCE MILLER, D.Sc., D.Eng., LL.D.

PROFESSOR OF PHYSICS

CASE SCHOOL OF APPLIED SCIENCE

WITH ILLUSTRATIONS

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PREFACE

The question of the influence of the material of which a wind musical instrument is made has not been settled after more than a century of widespread discussion. Is the tone quality of a flute, the tube of which is made of gold, superior to that of a similar flute made of silver or wood? If there is a difference, what is the explanation? It was this specific question that, in 1900, started the investigations which, having passed much beyond the original inquiry, have furnished the material for the reports here presented.

The desire to investigate the physical nature of musical sounds, and the sound-producing characteristics of musical instruments, led to a study of all available methods for recording the forms of sound waves. No device was found which was sufficiently sensitive and free from disturbing influences for the proposed investigations, and a new instrument, the "Phonodeik," was developed. Part I of this work describes the phonodeik, and the methods of using it, together with illustrations of phonodeik records of sounds of various types, such as voices, musical instruments, bells, fog horns, and the explosive sounds from large guns in action. A chapter is included explaining the photography of sound waves by the electric-spark method, as applied to the study of projectiles in flight and to the acoustics of auditoriums.

In 1918 and 1919 the writer organized, and carried out at Sandy Hook Proving Ground, an extended series of experiments on the pressure developed in the sound waves pro-

duced by the discharge of large guns, and for the determination of the velocity of the explosive sounds and of the normal velocity of sound in the free air. Preliminary reports have been presented to various scientific societies, but the reduction of the large amount of observational material has only recently been completed. A final report covering the several phases of these investigations is now presented as Part II of this work.

In the reduction of the observations, a least squares method of solving the exponential equations involved was prepared by Dean T. M. Focke, Head of the Department of Mathematics, Case School of Applied Science. The first calculations, extending over a period of a year, were made by the writer's Research Assistant, Mr. Ralph F. Hovey. The author's Research Associates, Professor John R. Martin, 1928, and Dr. Robert S. Shankland, 1932–33, have made the principal calculations relating to the final analysis and determination of the velocity of sound, and have assisted in the preparation of the manuscript. Professor R. S. Burington has given valuable aid. The author is especially indebted to Professor J. J. Nassau for advice and suggestions.

The author is under obligation to the Chief of Ordnance of the War Department and to the Commanding Officers of Sandy Hook Proving Ground for many privileges and courtesies extended in connection with the experimental work and the preparation of these reports. The Chief of Ordnance has given approval of the free use of all the scientific data obtained at the Proving Ground, and has provided the photographs reproduced in Figures 37, 57, and 63.

DAYTON C. MILLER.

CASE SCHOOL OF APPLIED SCIENCE,
CLEVELAND, OHIO,
MARCH, 1937.

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Chapter I

SOUND AND TONE QUALITY

Sound Waves

We *hear sound.* We hear many kinds of sounds, some pleasing, some very disagreeable; some sounds give useful information and some greatly annoy. What is it that is heard? We are interested in the physical nature of the phenomenon that thus gives pleasure or pain; not in how or why it is heard. Sounds belong to the world of reality, and exist, whether or not they are heard.

Aristotle, writing about 350 B.C., said: "Sound takes place when bodies strike the air, not by the air having a form impressed upon it, as some think, but by its being moved in a corresponding manner; the air being contracted and expanded and overtaken, and again struck by the impulses of the breath and the strings. For when the air falls upon and strikes the air which is next to it, the air is carried forward with an impetus, and that which is contiguous to the first is carried onward; so that the same voice spreads every way as far as the motion of the air takes place." Francis Bacon (1561–1626) remarks: "The nature of sounds hath in some sort been enquired, as far as concerneth music, but the nature of sound in general hath been superficially observed. It is one of the subtilest pieces of nature."

Lord Rayleigh (1842–1919) says: "The sensation of sound

is a thing *sui generis,* not comparable with any of our other sensations. Directly or indirectly all questions connected with this subject must come for decision to the ear, as the organ of hearing; and from it there can be no appeal. But . . . when once we have discerned the physical phenomena which constitute the foundation of sound, our explorations are in great measure transferred to another field lying within the domain of Mechanics. . . . Very cursory observation suffices to show that sounding bodies are in a state of vibration. . . . In the air of the atmosphere, sounds have a universal vehicle, capable of conveying them without break from the most variously constituted sources to the recesses of the ear. The passage of sound is not instantaneous."

The physicist uses the word *sound* to designate the vibrations of the sounding body itself, or the vibrations of the air or other medium, which are developed by the sounding body even though there is no ear to hear. The vibrations of the source produce various physical effects in the surrounding air, such as displacements, velocities, and accelerations, and changes of density, pressure, and temperature; because of the elasticity of the air, these displacements and other phenomena occur periodically and are transmitted from particle to particle in such a manner that the effects are propagated outward from the source. These disturbances of all kinds, as they exist in the air around a sounding body, constitute *sound waves.* Wave disturbances may be transmitted by solid and liquid as well as by gaseous matter; but the present study relates mainly to what may be heard and is limited to certain features of waves in air.

All that the ear perceives in the complex music of a grand opera or of a symphony orchestra is contained in the wave motion of the air consisting of periodic changes in pressure

or density and completely represented by motion of one dimension, that is, by motion confined to a straight line. That motion of one dimension is capable of producing these sounds is amply proved by the talking machine in which the backward-and-forward movements of a diaphragm are recorded and reproduced by direct mechanical connections. The amazing performances of radio microphones, amplifiers, transmitters, and loud-speakers, though requiring extremely complex apparatus, when properly interpreted, show that sound is, as Lord Kelvin has expressed it, "a function of one variable."

The physical characteristics of sounds are the loudness or intensity, the pitch or frequency, and the quality or tone color. The loudness depends upon the energy being transmitted by the sound wave and is related to the amplitude of the wave motion. The pitch is measured by the number of vibrations per second. The tone quality, sometimes called *timbre,* is a more complex property, represented by the "shape" of the wave; this characteristic of sound is perhaps the most interesting and it will be considered in detail.

The law of tone quality was first definitely stated, in 1843, by Georg S. Ohm, in *Ohm's Law of Acoustics.* This law states that all musical tones are periodic functions; that the ear perceives pendular vibrations alone, as *simple tones;* that all varieties of tone quality or tone color are due to particular combinations of a larger or smaller number of simple tones of commensurable frequencies; and that a complex musical tone or a composite mass of musical tones is capable of being analyzed into a sum of simple tones. Noise is due to a non-periodic vibration, or to a vibration which is too complex in structure or of too short duration to be analyzed or understood by the ear.

From these principles it follows that nearly all the sounds being studied are composites. The separate component tones are called *partial tones,* or simply *partials;* that partial having the lowest frequency is the *fundamental,* while the others are *overtones.* It sometimes happens that a partial not the lowest in frequency is so predominant that it may be mistaken for the fundamental, as with bells; and sometimes the pitch is characterized by a subjective beat-tone fundamental when no physical tone of this pitch exists. If the overtones have frequencies which are exact multiples of that of the fundamental they are often called *harmonics,* otherwise they may be designated as inharmonic partials. The understanding of the cause of tone quality and of the differences in tone color requires the analysis of a sound into its harmonics and partials.

The Analysis of Complex Sounds

The analysis of complex sounds by the ear alone, even when musically trained, is often difficult and uncertain. Helmholtz devised the spherical resonator to assist the ear. Rudolph Koenig improved the resonator, making it adjustable and tunable, and arranged a set of resonators each with a manometric-flame indicator, for studying eight or ten components of sound. Rayleigh arranged a delicately suspended disk in the opening of a resonator, making the method much more sensitive and providing for the quantitative measurement of the intensity of the sound. Recent investigators have used a series of Rayleigh disks simultaneously. The Rayleigh disk gives information concerning only those components of tone which are presumed to be present and for each of which a tuned resonator is pro-

vided. Observations by these methods are made directly upon the sound itself and usually do not require a record of the wave form.

Methods for directly observing and photographing the actual sound wave in air, which originated in the "Schlierenmethode" of A. Toepler (1864), are described in Chapter IV. When a wave consisting of compressions and rarefactions is being transmitted, there results a varying index of refraction of the air which is made visible by illumination with an instantaneous electric spark. The method is practicable only for sounds of short wave length and of considerable intensity; it is very useful for studying the propagation of sound waves near the source; it gives only indefinite indications of the wave form and is not suitable for the study of sounds in general.

The varied sounds of instruments and combinations of instruments, of voices uttering vowels and words, of explosions, and the sounds of nature are all produced by the pressure waves in the air, each kind of sound having its own characteristic mode of pressure change. If the variations of pressure of the air through which a sound wave is passing, are charted with respect to time, or are recorded by a sensitive instrument, there results a "curve" which is a graphic representation of the sound wave. The records of the pressure changes of the sounds from the various sources contain the complete information defining the characteristics of these sounds. The height or amplitude of the record of the sound wave characterizes the intensity of the sound; the pitch of the sound is determined from the number of fundamental wave lengths per unit of time; the shape of the wave is representative of the quality or tone color of the sound. While inspection and simple measurement often will

give some information concerning these curves, they are in general too complicated for interpretation in their original forms, and several methods have been developed for their analysis.

A method of analysis which is practically complete and entirely adequate, for *periodic curves* only, that is, for the records of musical sounds, is based upon a combination of Ohm's Law of tone quality with the mathematical principle known as *Fourier's Theorem,* first published in 1822, by Baron J. B. J. Fourier of Paris. This method is commonly referred to as *harmonic analysis.* Fourier's Theorem shows that any periodic curve which is finite and continuous and single valued, however complicated, can always be analyzed into a definite series of simple sine curves. Since the graph of a simple tone is a sine curve, the graph of a compound tone is a periodic complex curve; it follows, conversely, that the sine-curve components of a record of a compound tone are correct quantitative representations of the harmonic components of the tone. The mathematical harmonic analysis of a sound wave is a precise definition of its tone quality. This method is *not* applicable to non-periodic functions of any kind, and the attempt to apply the Fourier method to such functions leads to erroneous conclusions. The Fourier analysis of a curve may be carried out by numerical calculation which becomes very laborious for a curve with many components. Several mechanical *harmonic analyzers* have been devised which greatly facilitate the operations. A detailed explanation of the processes and of analyzers, synthesizers, and subsidiary apparatus for complete harmonic analysis has been given in other publications by the author,[1,16] and need not be repeated here.

Chapter II

THE PHONODEIK

Recording Sound Waves

The principal methods which have been developed for recording sound make use of a diaphragm as the sensitive receiver. A diaphragm is a thin sheet or plate of elastic material, usually circular in shape, supported more or less firmly at the circumference. Diaphragms respond with remarkable facility to tones of a wide range of pitch and to an almost unlimited variety of tone combinations. The performances of the present-day radio broadcasts and receptions amply verify this fact. The usefulness of the diaphragm is often limited, and sometimes nullified, both for scientific and practical purposes, by certain peculiarities in its action, called distortions, which are related to resonance or natural periods. One of the early diaphragm methods for recording sound waves is the Scott-Koenig Phonautograph (1857), which records the vibration curve directly on smoked paper.[2] The development of this method led to the making of minute up-and-down records of the vibrations of the diaphragm in wax, as in the Edison phonograph of 1877.[3] Emile Berliner made transverse records of the vibrations, etched in zinc, and produced the gramophone in 1887.[4] Such records have been enlarged for analytical study by L. Bevier,[5] E. W. Scripture [6] and others. Rudolph Koe-

nig devised the manometric capsule with which the vibrations are made visible by vibrating flames,[7] and E. L. Nichols and E. Merritt, and J. G. Brown, have photographed such flames.[8] The telephone of Alexander Graham Bell[9] develops electromagnetic variations corresponding to the vibrations of a diaphragm, and by means of the oscillograph of A. Blondel and of W. Duddell,[10] the wave form may be photographically recorded. A. G. Webster, in the phonometer, applied the method of the Michelson interferometer photographically to record the vibrations of a diaphragm.[11] Various recent methods for recording sound waves are described by F. Trendelenburg,[12] and a special technique has been developed in connection with the talking motion-picture.[13]

For the investigation of the tone quality of musical instruments, a permanent graphical record of the wave form of the sound seemed necessary; none of the methods for recording sound was sufficiently sensitive and free from influences producing distortion of the wave form. The only hope of progress seemed to lie in the adoption of a diaphragm apparatus with a mechanical-photographic arrangement for recording the vibrations of the diaphragm, and in developing the method to the highest possible sensitivity. The first experiments were made with a phonograph sound-box with a mirror and light-spot arrangement, the mirror being connected to the diaphragm by a system of delicate levers which would transmit the magnified movements of the diaphragm to the mirror, and photographic records of sound waves were made with such an arrangement in 1903.

In 1908 a new instrument was devised, the plan of which is shown in Fig. 1. The receiver is a collecting horn *H*, the small end of which is closed by a sensitive diaphragm *D*.

A minute steel spindle is mounted in jeweled bearings near the diaphragm; a tiny mirror *M* is attached to the spindle; the lower end of the spindle is fashioned into a small pulley. A few fibers of untwisted silk are attached to the center of the diaphragm, are wrapped once around the pulley, and are fastened to a delicate spring *S*, which keeps the fibers under tension. Light from a pin-hole source *P* is focused by a lens *L* and reflected by the mirror *M* to a moving film in a special camera.

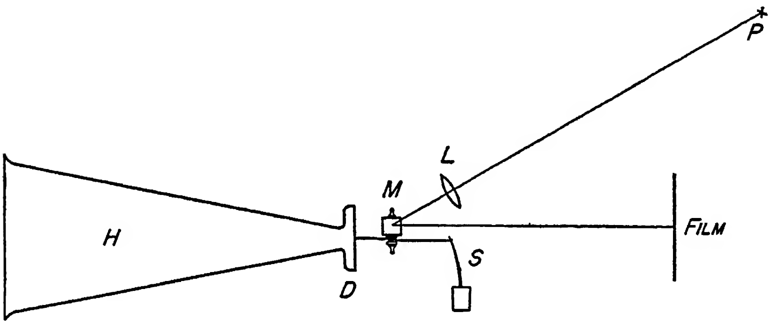


FIG. 1. Principle of the phonodeik.

The movements of the diaphragm under the action of a sound wave give angular displacement to the mirror, and the light-spot traces the shape of the sound wave in a greatly magnified form on the photographic film. Photographs of sound waves made with such an apparatus were first exhibited at the Baltimore meeting of the American Physical Society and the American Association for the Advancement of Science in December, 1908, and at the Winnipeg meeting of the British Association for the Advancement of Science in August, 1909.[14] A modified form of the apparatus was arranged for demonstrations before a large audience and both the photographic and the demon-

stration types of the instrument were exhibited at the Boston meeting of the American Physical Society and the American Association for the Advancement of Science in December, 1909.[15] The name "phonodeik" (to show sound),

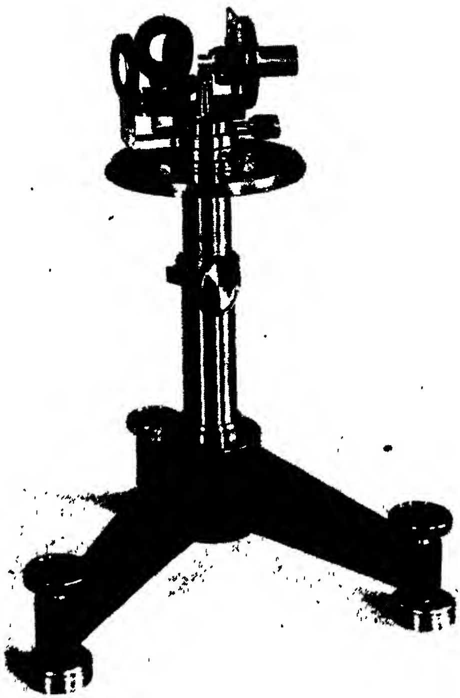


FIG. 2. The Photo Phonodeik.

suggested by the late Professor Edward W. Morley, was first applied to the device at the Boston meeting.

The phonodeik in the form used for photographic study is shown in Fig. 2, and in the center of the assembled apparatus in Fig. 5. Some details of a vibrator, of similar design, are shown in Fig. 9.

Mechanical Principles of the Phonodeik

The ultimate purpose of the phonodeik is to produce a photographic record of a sound wave of such a size and of such definiteness and accuracy of outline as shall permit the quantitative study of waves having components of small magnitude and high frequency. The peculiarities of each part of the apparatus were investigated for efficiency, and the results were embodied in the final design.

A horn greatly influences the response of the diaphragm, due to the resonance properties of the body of air enclosed by the horn; these effects depend largely upon the volume of the enclosed air, and in a lesser degree upon the shape of the horn and upon the character of its inner surface. It is often advantageous to adapt the size and shape of the horn to the particular frequency or range of frequencies and to the intensity of the sound being recorded. For use with the phonodeik a variety of horns is provided, of conical, exponential and other shapes. These horns vary in length from 13½ inches to 6½ feet. Each horn has its own natural frequencies, consisting of a fundamental and a series of overtones, to which it responds with exaggerated intensity. These natural tones can be produced by blowing with a mouthpiece as in a bugle. The fundamental frequency can be heard by tapping the small opening with the palm of the hand. A long horn responds nearly as well to high frequencies as does a short horn, while the response to low tones is much greater; the response below the fundamental of the horn is very feeble. The horn selected should be of such a length that its fundamental is lower than the lowest tone under investigation. The methods for determining the effects of a horn and for correcting the records are considered

in a later section, and are treated more extensively in "The Science of Musical Sounds," pages 156-174.[16]

When a diaphragm responds to a simple sound it vibrates in one or more zones which may be referred to as the Chladni zones. The amplitude of the movement of the diaphragm depends upon the mass and elastic properties of the material and upon its dimensions and manner of support. The amplitude increases with the size of the diaphragm so long as the edge of the diaphragm lies within the boundary of a single Chladni zone. When, however, the size of the diaphragm is such that the area enclosed by Chladni nodal lines lies wholly within the boundary of the diaphragm, then further increase in size will not greatly increase the amplitude of the diaphragm movement.

Experiments were made with diaphragms of several sizes and thicknesses and of various materials, such as iron, steel, copper, glass, mica, rubber, gelatin, paper, albumen, and soap film, and with various types of mounting and housing for the diaphragm. In order to obtain sensitiveness to high-pitch sounds, very thin glass was selected, such as "cover-glass" used in mounting microscope objects, having a thickness of 0.08 millimeter (0.003 inch). With this thickness, and the method of mounting to be described, and for sounds of frequency of 200 and over, a diameter of 32 millimeters seems suitable. For lower frequencies, a larger diameter of diaphragm may be used, though this is not necessary since the vibrations of lower frequency are usually of relatively large amplitude and the response may be calibrated in any case as described elsewhere. If thicker glass is used, or other material of greater rigidity, a suitable diameter may be found by trial.

The diaphragm must be retained in a definite position,

and it must form an air-tight sound-box on the end of the horn. At first it was thought desirable to have the diaphragm firmly cemented to a glass sound-box. The rigid edge reduced the sensitiveness so much that this was abandoned and the diaphragm is now placed between rings of the softest rubber, about 1 millimeter thick, and is held to its support by a screw ring which clamps it as lightly as possible and at the same time secures air-tight closing around the edge. Further details of the diaphragm experiments have been given in "The Science of Musical Sounds," pages 142-156.[16]

The usual displacement of the diaphragm for sounds of ordinary loudness is about half a thousandth of an inch, resulting in an extreme movement of one thousandth of an inch (0.025 millimeter). This movement of the diaphragm of a thousandth of an inch must include the small variations of motion corresponding to the fine details of wave form which represent musical quality. Many of the smaller kinks shown in the photographs, as in *G*, Plate II, and *O*, Plate IV, are produced by component motions of the diaphragm of less than one hundred-thousandth of an inch; the phonodeik must faithfully reproduce and record not only the larger and slower components but also these minute vibrations which have a frequency of perhaps several thousand vibrations per second.

The magnification of the phonodeik depends upon the diameter of the pulley on the mirror staff and upon the distance of the mirror from the film. A smaller size for the pulley results in a greater angular motion of the mirror for a given displacement of the diaphragm, and consequently permits a shorter distance to the film for a given magnification. Further, a minimum distance of film permits the use of a

mirror of minimum area. It was decided to employ a magnification of 3000 times, resulting in a record on the photographic film 3 inches wide, for a movement of the diaphragm of a thousandth of an inch; the film commonly used is 5 inches wide, providing for abnormal displacements. The smallest practicable pulley seemed to be one having a radius of 0.3 millimeter, and a face width of 0.2 millimeter. With such a pulley, a displacement of the diaphragm of a thousandth of an inch produces an angular displacement of the mirror of 4.85°, and twice this displacement for the reflected beam of light. To obtain a magnification of 3000, the mirror must be about 17½ inches from the film.

The determination of the minimum area of the vibrating mirror which will give the proper light intensity on the photographic film involves a study of the spectral characteristics of the light source, the color sensitivity of the photographic emulsion, and the selective reflectivity of the small vibrating mirror.

The light source is a direct-current arc, with carbons mounted at right angles and with an automatic feed. Photographic tests were made with electrodes of various materials as well as with carbons which had been treated to secure greater brilliancy. A high grade carbon, as developed for motion picture projection, gave the best results. The positive carbon is 9/16 inch in diameter, and the negative is a cored carbon 7/16 inch in diameter. A super-voltage is applied sufficient to produce a current of about 30 amperes, and the lamp is provided with magnetic coils to prevent the magnetic blow which is troublesome with large currents when the electrodes are at right angles.

The virtual source of light is a pin-hole in a piece of sheet iron. The pin-hole is directly illuminated by the

naked arc, which is placed behind the iron plate, and as near as may be without undue heating. It makes no difference how far from the hole the arc is, so long as the heated crater is large enough to fill the solid angle of the cone of light which can be focused on the film. It is desirable to have the iron plate held in a massive support to dissipate the heat and prevent too rapid oxidation; and the arc should be so far from this support that it shall not be appreciably cooled by conduction of heat by the metallic mass. In the phonodeik the arc is located one inch from the pin-hole.

The light-spot which traces the curve on the film is the image of the illuminated pin-hole. The diameter of the spot should be a minimum for sharpness of tracing, and a maximum for photographic effect. A diameter of the spot of 0.5 millimeter was adopted as suitable for records from 3 to 5 inches wide. With records of this size the light-spot often will have a speed of 1000 feet per second in tracing the curve on the photographic film, and the time of photographic exposure will be only 1/600,000 second. A superspeed ortho portrait film has given the best record as regards definition and contrast. The lowest speed of the light-spot, occurring at each "turning-point" on the wave, is the lineal speed of the moving film.

Experiments were made with various mirrors coated with silver and with other materials giving greater intensity in the violet and ultraviolet regions. It was found that, using an arc of highest visual intensity, the integrated photographic effect was greatest with a silver-on-glass reflecting surface. By locating the mirror as near as practicable to the photographic film, the required area of reflecting surface will be a minimum. With the film distance adopted, 17½ inches, a minimum area of 3 square millimeters of reflect-

ing surface would throw sufficient light onto the film to leave a just perceptible record with the given size and maximum speed of light-spot; for slower speeds (lower frequencies) the record would be more dense and entirely satisfactory for analytical study.

The vibrator, consisting of the spindle and the attached mirror, should have the greatest possible dynamic delicacy in order that it may respond to the desired range of frequencies; it should have a minimum moment of inertia, and a minimum of friction and of lost motion. The conditions already determined require a pulley on the staff 0.6 millimeter in diameter and 0.2 millimeter between the flanges, and a mirror having an area of 3 square millimeters; if this mirror is of glass 0.08 millimeter thick, its mass will be 0.7 milligram. The "staff" of the balance wheel of a watch gave the first suggestion for the design of the vibrator.

Professor Edwin C. Kemble, then a senior student in Case School of Applied Science, undertook for his graduation thesis the formation of the differential equations involving the dynamic conditions as these relate to the amount and distribution of glass and of steel in the moving parts of the phonodeik, and solved the equations for the condition of minimum moment of inertia for the range of frequencies of audible sounds. This study led to the adoption of the shapes and dimensions described in the following paragraph.

The glass for the mirror has a length of 1.9 millimeters in the direction of the axis of rotation and is 1.6 millimeters wide. The steel staff is shaped as shown in Fig. 3, so that the axis of inertia of the mirror and staff is in the axis of rotation; this portion of the staff is 2.0 millimeters long, 0.6 millimeter wide, and 0.1 millimeter thick. At the lower end of the staff is the pulley for the silk fibers,

having the given diameter of 0.6 millimeter and a face width of 0.2 millimeter. The pivots are each 0.1 millimeter in diameter. The over-all length of the staff is 3.3 millimeters and its mass is 2.02 milligrams.

The staff is mounted in sapphire jewels in the manner of the balance-wheel staff of a fine watch, the jewels being held in a bronze block and cap, Fig. 3. The pivots are cylin-

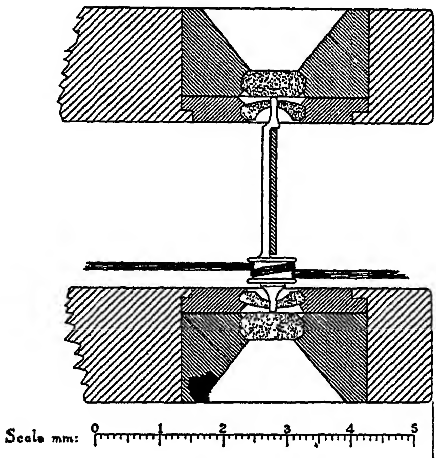


FIG. 3. Mirror staff and jeweled mounting.

drical and fit the holes in the hole-jewels perfectly; the cap-jewels, with plane surfaces, permit a very slight end movement. No oil is used, for this would necessitate a loose fit to allow a film of oil to be present. The oil would be a serious disadvantage as it would act as a "shock absorber" for the vibrations of high frequency and small amplitude, and the oil space would allow the staff to wobble enough to ruin the record with a magnification of 3000. It has been found desirable first to make the pivots a tight fit and then to polish them carefully till a perfect, easy fit is secured.

The cover glasses for the mirrors are selected from stock by optical interference methods, using a test plane and sodium light to determine flatness. The mirrors are used through the glass. After silvering, the silver surface is coated with a thin film of soft wax, or is "aluminized," to prevent tarnishing. The silvered cover glass is cut by means of a diamond on a dividing engine into rectangles of the required size, 1.6 x 1.9 millimeters. A single cover glass will yield perhaps fifty of the small mirrors. These are then sorted by actual trial in the phonodeik camera, with the result that about one in ten of the mirrors will be found to give a concentrated, circular, well-defined image of the light-spot, suitable for use. The mirror is attached to the steel staff by means of soft wax; care is necessary to avoid warping of the mirror by the wax; a very small "spot" of wax applied near one edge of the glass has been found effective.

The vibrator is connected to the diaphragm by a "bundle" of untwisted silk fibers, four or five in number, the mounting of which is a delicate operation. A minute eyelet of aluminum foil or wire is cemented to the center of the glass diaphragm, and the fibers are tied to the eyelet by a single knot; the knot is made secure by a touch of wax or shellac applied by means of a heated wire. To prevent breaking the thin glass diaphragm, it has been found helpful to begin by cementing one end of the bundle of fibers to a very slender thread of soft rubber cut from a piece of dentist's rubber dam, and to manipulate the bundle by the rubber thread, thus avoiding undue pressure on the glass or vibrator. The bundle of fibers is threaded once around the pulley on the staff, in such a direction that a positive pressure of the sound wave on the diaphragm will cause the mirror to displace the spot of light on the photographic film in the

direction of positive ordinates of the final record of the sound wave. The fibers must be kept under constant tension, just sufficient to prevent slipping of the vibrator; a tension of one gram weight has been adopted. This tension is provided by a delicate flexural spring, *S*, Fig. 1, made from a piece of fine watch hair-spring. The spring is 6 millimeters long, 0.14 millimeter thick, and 0.18 millimeter wide; it is clamped at one end and has a natural frequency of about 6000; the fibers are attached to the free end by a drop of melted shellac. To secure a proper and uniform tension, a weight of one gram is hung on the free end of the rubber thread while the fibers are being cemented to the spring. The superfluous fiber with the rubber thread is cut off close to the spring. The tension of the spring may be adjusted by means of a screw in the mounting of the spring *U*, Fig. 9. A shield is placed around the spring to prevent accidental injury.

Instead of the flexural steel spring, the slender rubber thread attached to the fiber may be attached to a fixed part of the mounting; the rubber, however, soon deteriorates and must be frequently replaced. A spiral spring of wire, however fine, has too great an inertia for use with the high audio-frequencies.

The reflected light-spot may be brought to the center line of the film by slackening the tension of the spring and slipping the pulley on the fiber. In order to secure accurate adjustment of the light-spot to the zero axis of displacements, the mounting for the vibrating mirror is supported on a flat plate attached to the diaphragm ring at one edge so that it may be flexed by an adjusting screw *V*, Fig. 9. The effect of turning the screw is to move the pulley along the fiber, producing slight rotation.

Optical Principles of the Phonodeik

In designing the optical parts of the phonodeik, the fulfillment of one requirement may destroy another, and critical adjustment of advantages and disadvantages must be made. The fundamental principle was applied that no system of condensing lenses can produce a light-spot of greater intrinsic brilliancy than the original source itself. With the carbon arc light, the area of bright carbon of maximum brilliancy is always larger than can be made use of in the very narrow optical angle of the apparatus, and there is no need of a lens system either to converge or to parallelize the rays of light.

The greatest efficiency will be secured when the focusing lens is midway between the source and its image on the film, the pin-hole and image being of equal size. Under these conditions the air path is the least possible, the lens may be of minimum thickness, and the dimensions of the whole apparatus will be as small as possible. The mirror must be between the focusing lens and the film, and it is most efficient in light-gathering capacity when it is as near as possible to the lens. Considerations of mechanical design place the lens 1½ inches from the mirror, and the desired magnification of 3000 requires that the mirror be located 17½ inches from the film; thus the lens is 19 inches from the film, and is at the same distance from the illuminated pin-hole, and the required focal length is 9½ inches.

The diameter of the lens needs to be only sufficient to furnish a beam of light covering the near-by mirror which is less than 2 millimeters in its largest dimension. Since a larger lens facilitates adjustment, and as the beam of light

must also cover the stationary mirror, for the zero line mentioned later, the actual diameter of the lens in use is $\frac{5}{8}$ inch. It is a two-piece achromatic lens of the thinnest construction. The optical angle is so very small that a single non-achromatic lens would serve nearly as well.

It is further desirable that the light should be reflected from the vibrating mirror at as near perpendicular incidence as is possible; this not only secures the maximum efficiency in reflection from the silver, but also utilizes the area of the mirror to the greatest advantage and reduces to a minimum the loss due to reflection at the glass surface and to absorption in the glass. The angle of incidence is 15°, giving an angle of 30° between the direct and reflected rays.

The phonodeik as actually constructed is operating at the extreme limit of efficiency, with no considerable "factor of safety"; that is, each contributing factor must be used to its fullest capacity. If the pin-hole is made larger, more light will pass through, but to keep the light-spot of the same size as before, the lens must be placed farther from the hole (and must have a different focus), and in this case the mirror (the size remaining constant) will receive less of the light in just the proportion by which the enlarged hole gave increased light. Conversely, if the mirror and lens are placed nearer the hole, the mirror will receive more light, but in order to preserve the same size of spot, the hole must be made smaller. And further, when the hole is too small diffraction effects are introduced.

It would seem that in order to make a more sensitive photographic record it will be necessary to have: (a) a more intense light source; (b) a better reflector; (c) a more sensitive film; and until one, or more, of these things is pro-

vided, it will be impossible to produce records capable of showing finer detail.

Auxiliary Records—Time Signals and Axis

In the early experiments an effort was made to produce the sound at a predetermined pitch by comparison with a piano, organ, or tuning fork; but often it was difficult to set and maintain the pitch throughout the test. It was found much more convenient and accurate to produce the sound at convenience, and to determine the pitch by recording the speed of the film. For this purpose a large stroboscopic fork of Koenig's make, *F*, Fig. 5, having a frequency of 50 cycles per second, is arranged to produce minute flashes of light at the rate of 100 per second; these flashes are reflected to the film by an adjustable small mirror and a focusing lens which are mounted on the vibrator stand.

Attached to each prong of the fork is a thin aluminum plate. These plates overlap, but do not touch. In one plate is a very fine opening in the form T, while in the other is a fine slit |. These openings are so adjusted that when the fork is stationary the two slits coincide; when the fork vibrates they coincide at the middle of each vibration and allow light to pass, but at other times they mismatch and no light passes except through the cross slit; the result is a series of signals which lie on the film in this form T T T, and mark points corresponding to intervals of 1/100 second. The period of the fork is adjustable by means of sliding weights, on the graduated prongs; it can be rated by photographing the sound of a standard fork and counting the waves between flashes, or by recording the beats of a standard clock and counting the flashes per second. The fork is maintained in vibration by Koenig's usual electromag-

netic drive. Such time signals appear on most of the photographs of sound waves shown in later sections.

For the purposes of harmonic analysis it is not necessary that the true axis of the curve shall be known, but it is required that a line parallel to the axis be determined to serve as a base for the analysis. A line passing through points in successive waves which are in the same phase, such as the tips of successive peaks, is such a line. It is often convenient to have a line on the record which is near to the true axis. For recording such a line, a small mirror, of the same size as the vibrating mirror, is placed on a stationary holder in a position just below the vibrating mirror. This mirror is adjustable so that when the light passing through the lens falls upon it, this second spot of light is reflected to the film at the same place as is the vibrating spot when the latter is in its zero position (position for quiet). If this condition is accurately fulfilled, the trace will be the true axis; if the adjustment is only approximate, the line will still be parallel to the axis and will serve the purposes of analysis. Such a zero line is shown on several curves in Plates III and IV.

When a photograph is desired for display, the zero line may be omitted while the time signals are still recorded; this arrangement is found in most of the records shown in this work. A line drawn through the horizontal parts of the time-signal T's is a line parallel to the axis of the curve, and is used for the analysis.

The true axis of a phonodeik curve may always be found, whether or not the zero line and time signals are recorded, by means of measurements made with a planimeter. The procedure is explained in "The Science of Musical Sounds," page 107.[1]

The Phonodeik Laboratory

In studying the nature of sounds, it is, of course, the sound as it is originally produced at the source that is of first interest. Sounds, as heard by the ear, are usually much modified by the surroundings. Perhaps a sound-recording instrument might best be used out-of-doors, as on the roof of a building, to avoid disturbances due to reflection, interference, absorption, etc. Since it is not convenient to work in such a place, the disturbances of an enclosure are minimized by various precautions such as acoustic treatment of the walls, the suitable location of the source and recording apparatus, and by the use of sound screens. A plan of the phonodeik apparatus for studying sounds is shown in Fig. 4, and Fig. 5 is a view of the phonodeik laboratory.

The ceiling and side walls, including door and windows, are treated with acoustic material of the highest absorptive quality, giving a reverberation time for the room with its equipment in place of about 0.2 second for the frequency of 512. A further precaution consists in placing thick rugs on the floor and in covering exposed apparatus with heavy felt blankets. A sound-opaque screen is placed between the vibrator and camera to protect the receiving apparatus from any noise produced by the arc, motor, or revolving drum; the moving parts of the apparatus are, however, practically noiseless.

The phonodeik vibrator consisting of the diaphragm, the small mirror and the two focusing lenses, previously described, is located at V, Fig. 5; H is the exponential collecting horn; A is the arc lamp with the pin-hole attached to the front of the housing; the current for the light is controlled by the rheostat R_1; F is the large tuning fork, pro-

vided with a light for projecting the time signals, which are reflected to the film by an adjustable small mirror mounted on the vibrator stand. The camera, X and Y, consists of a stationary part containing the mirrors for visual observation and the shutters, and of several interchangeable film boxes.

For visual observations the camera is arranged with a

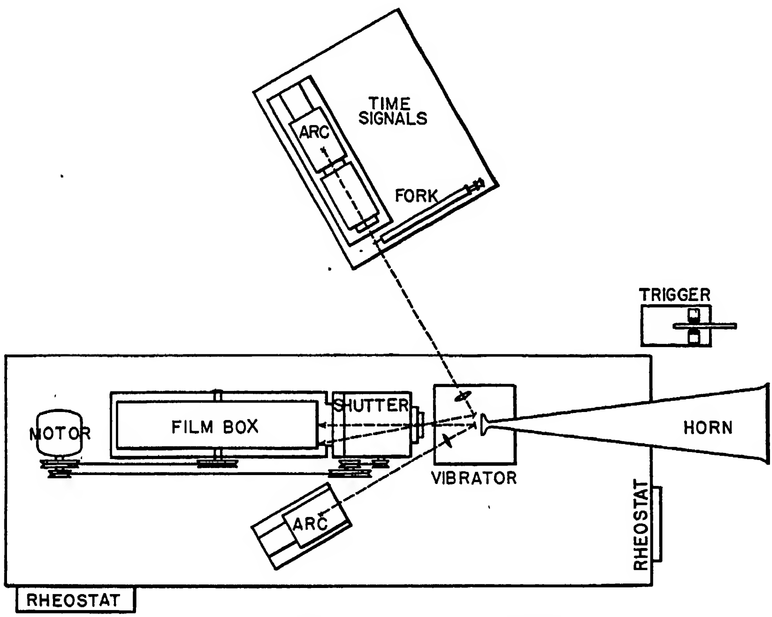


FIG. 4. Plan of phonodeik apparatus

horizontal four-sided, revolving mirror which reflects the vibrating light-spot upward on a ground glass G, in the form of a wave; an inclined stationary mirror above the ground glass makes the wave visible to the experimenter while the sound is being produced. The speed of the revolving mirror and the dimensions in general are so proportioned that the wave appears on the ground glass in the same size and form as when photographically recorded. The speed of the

motor may be adjusted till the wave appears satisfactory and the film speed will be automatically varied to correspond; the sound is altered in loudness or quality as desired; when a suitable wave appears on the ground glass, the closing of the electric key or the pressure of the foot on the floor trigger makes the photographic exposure.

FIG. 5. The phonodeik laboratory.

There are two shutters: S_1, a diaphragm shutter for time exposures, and S_2, a focal plane shutter for short exposures. Three separate releases are provided for these shutters; a single-contact key K which can be moved to any convenient location; a trigger release T_1 on the floor, to be operated by the foot of the observer as he sees the wave form on the ground glass G; an electromagnetic trigger T_2 which is oper-

ated by electric contacts on the revolving drum, or by other suitable apparatus as required.

The camera is arranged for films 5 inches or less in width and of lengths to 100 feet; there are three film boxes with revolving drums, turned by motor, having circumferences of 1, 2, and 5 feet (*Y*, Fig. 5) respectively; another box contains a pair of drums, each holding 100 feet of film, arranged for winding the film from one drum to the other by hand during exposure.

The photographs are all taken under such conditions that the time scale of abscissas reads in the positive direction from left to right, and so that a positive ordinate of the curve corresponds to the compression part of the air wave.

Since various speeds of the film are desirable, a variable-speed motor *E* is used, and the film speed is determined by measurement of the time signals which, being photographically recorded, furnish a permanent record of the speed of each separate film. The motor is unusually well balanced, and its operation is practically noiseless. To avoid any possibility of noise or vibration, the motor rests in a "sling" of leather straps, and the box supporting the straps rests on a sheet of thick acoustic felt.

The rheostat, R_2, for controlling the speed of the motor and of the film and revolving mirror is placed where it can be reached by the experimenter when he stands near the horn, and there is visible a tachometer *Q* which indicates the momentary speed. For general display pictures a speed of 5 feet per second is convenient, while for records to be analyzed 40 feet per second is suitable; for the latter purpose a short record 1 or 2 feet long, made in 1/40 or 1/20 of a second, is sufficient.

The Projection Phonodeik

For lecture demonstrations a phonodeik, Fig. 6, has been designed which will clearly exhibit the principal features of "living" sound waves.[15] The sound from a voice or an instrument is produced in front of the collecting horn; the resulting movement of the diaphragm with its vibrating mirror displaces the light-spot in a vertical direction, and the light-spot falling upon a motor-driven revolving mirror is reflected to the screen in the form of a horizontal wave. The movements of the diaphragm are magnified in proportion to the distance of the screen; a magnification of 25,000 times or even 40,000 times is practicable, producing a wave which may be 10 feet wide and 40 feet long. As seen on the screen the sound waves are constantly in motion, changing shape and size with the slightest alteration in frequency, loudness, or quality of the source. When the revolving mirror is kept stationary, the spot of light on the screen moves in a vertical line only, and illustrates the principle that sound is a function of only one variable.

The diaphragm, *D*, and steel staff are of the same dimensions as those used in the photo-phonodeik. The vibrating mirror of the photo-phonodeik having an area of 3 square millimeters, is too small to make the waves visible on a large screen; for the demonstration phonodeik the mirror has an area of 6 square millimeters, the dimensions being 2 x 3 millimeters. With the larger mirror, the effect of air-damping is noticeable and the upper frequency limit is about 3000 cycles per second; however, this gives ample range for demonstrations.

The virtual source is an illuminated pin-hole, 1.3 millimeters in diameter, in a piece of sheet iron, mounted in an

adjustable support at *P*, Fig. 6. The source of light is a small carbon arc-lamp *A*, with an automatic feed, requiring a direct current of about 10 amperes. It is the type of lamp

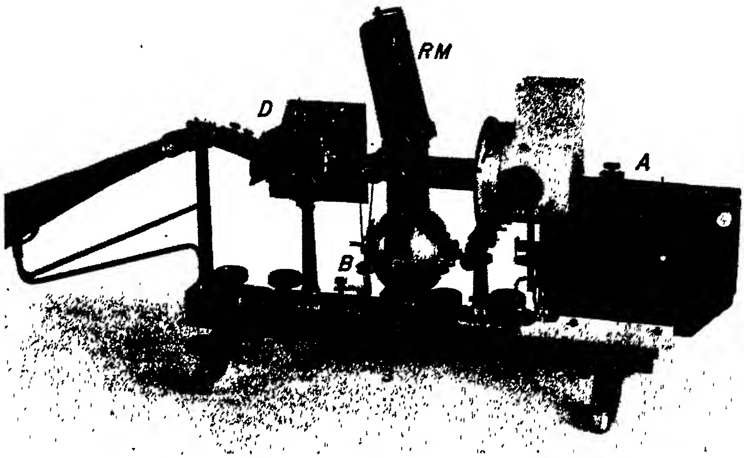


FIG. 6. Projection phonodeik.

used for microscope illumination. No condensing lens is used with the arc.

For the demonstration phonodeik the effective optical angle is increased without a large mirror by the use of a

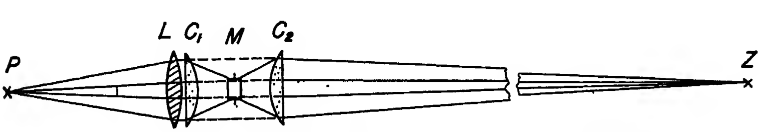


FIG. 7. Condensing system of projection phonodeik.

special condensing system of two plano-cylindrical lenses near the vibrating mirror. In Fig. 7, and in Fig. 6, *P* is the pin-hole source, *L* is the focusing lens, of 6¼ inches focal length, and *M* is the small vibrating mirror, 2 x 3 millimeters in size, located about 2 inches from the lens. *Z* is the screen

at a distance which may be 12 feet, more or less. With this arrangement the optical angle is limited by the dimensions of the mirror. Since the mirror has no displacement in a plane containing its axis of rotation (the steel staff to which it is attached), it is possible to introduce two equal plano-cylindrical lenses, C_1 and C_2, on opposite sides of the mirror, so that a greatly increased optical angle with increased illumination is secured, *in the direction of the axis only,* and without interfering with the action of the focusing lens and mirror in forming the image of the vibrating spot on the screen. The cylindrical lenses have a focal length of 2 inches. In order to secure simplicity in the lens system and to eliminate two glass surfaces, the focusing lens L and one of the cylindrical lenses C_1 are combined in a sphero-cylindrical lens. When the light-spot is first focused it will usually appear elliptical in shape; by adjusting the second cylindrical lens C_2, the elliptical spot can be brought to a properly defined circular spot.

The revolving mirror *RM,* Fig. 6, has four reflecting surfaces. The wave on the screen is merely the trace of the small circular image of the illuminated pin-hole, which appears to be a continuous wave-line because of the persistence of vision. The speed of the revolving mirror must be such that traces of the wave form by successive sides of the mirror shall not follow each other so rapidly that several images of the wave will appear simultaneously. About four revolutions per second, giving sixteen images, is the proper speed, though there can be considerable variation without noticeable effect. It is thus possible to adjust the speed of the mirror somewhat to accommodate longer or shorter wave-lengths, making details more apparent. The mirror is rotated by a small, universal motor, in an alumi-

num case, nearly spherical in shape and about 3 inches in diameter. The speed of the motor is controlled by a friction brake *B*; the belt pulley on the motor shaft is as small as practicable, about ½ inch in diameter. It is convenient to operate the motor from the same current-supply as is used for the arc lamp. A series resistance coil R_3 in the motor circuit is located under the base of the instrument and suffices to regulate the motor speed with voltages varying from 50 to 120 volts.

Various collecting horns may be used depending upon the particular kind of sound being projected. The most generally useful horn is one of simple conical shape, 24 inches long, and 6 inches in diameter at the large end. It is mounted with a flexible joint so that it may be moved to pick up the sound most effectively.

This phonodeik has been designed for portability; the base is of aluminum and is 16 inches long; the complete instrument, including the horn, weighs 13 pounds.

The Portable Phonodeik

In 1917 photographic records were made of the sounds from a fog horn at Father Point, Quebec;[17] two of these photographs are shown in Plate V. The laboratory phonodeik was used, on land and on shipboard, at various stations distributed over a distance of three miles from the fog horn. In 1918 an extended series of observations of the sounds from large guns was planned, to be made at Sandy Hook Proving Ground. Records were to be made near the guns, of explosive sounds of great intensity, and at distances of several miles where the sounds would be of minimum audibility. Taking advantage of the experience gained in the

observations at Father Point, a new form of portable phonodeik, Fig. 8, was designed, especially adapted to field conditions as found at Sandy Hook and other non-laboratory stations.

The portable phonodeik is arranged to be used with film boxes of three different types, depending upon the purpose

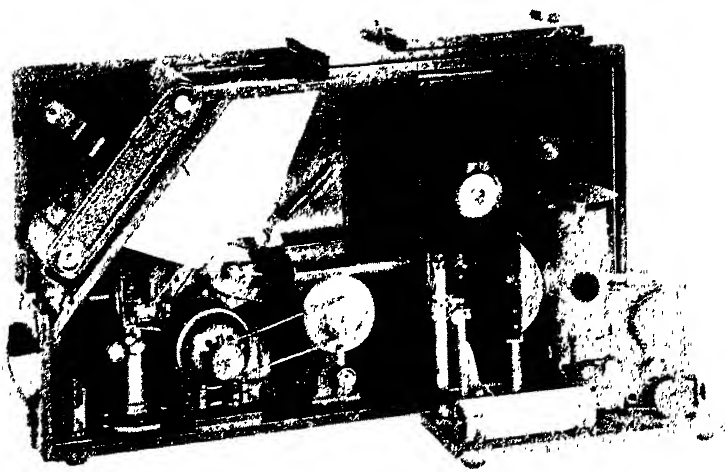


Fig. 8. Portable phonodeik.

for which the record is desired. All the boxes take roll film, 2¾ inches wide or narrower. The power required is a connection to a lamp socket in the usual 110-volt lighting circuit. The apparatus for making records of ordinary sound is contained in a case which measures 22 x 12½ x 5½ inches, and is no larger than an ordinary suitcase, the total weight being about 17 pounds.

For obtaining a record of the wave form of a continuing sound, a stationary film in connection with a revolving mirror is suitable. The film box is the body of a hand camera of common type, with the bellows and lens board removed, and with a slide added to close the box; such a camera box is shown in the upper left corner of Fig. 8. The camera box can be removed for loading and unloading; it uses the ordinary film "cartridge" and is "daylight loading." The length of film exposed at one time is always the same, 4¼ inches.

In the top of the case, adjacent to the film box, is a ground glass on which may be seen the wave form, zero line, and time signals as they will appear on the film. The record of the waves can be extended or condensed by varying the speed of rotation of the revolving mirror by means of the motor control, thus producing a wave length which is proper for analysis of the wave form.

The source of light is a small carbon arc-lamp, requiring a current of about 10 amperes, provided with adjustments for centering the arc. Immediately in front of the arc is the pin-hole, a hole 0.5 millimeter in diameter in a piece of sheet iron. The light from the pin-hole passes through the focusing lens *L*, Fig. 9, to the small vibrating mirror *M*, and is then reflected to the rotating mirror, and is focused, as seen on the ground glass, by adjusting the position and distance of the arc and pin-hole.

The revolving mirror has only one reflecting face, in the axis of rotation; it is rotated by means of a small electric motor placed on the bottom of the case. The motor drives a counter shaft on which are several pulleys for variable speeds and for driving the other film boxes. The speed of the motor is controlled by a friction brake. For visual observation only, it is sometimes desirable to substitute for the

single-face revolving mirror a four-faced mirror giving a more continuous wave on the ground glass.

A special type of shutter was designed for this particular apparatus; the exposure is made automatically by means of a cam on the spindle of the revolving mirror, so that only a single flash of the wave is recorded, whatever may be the speed of revolution of the mirror. The cam action, making

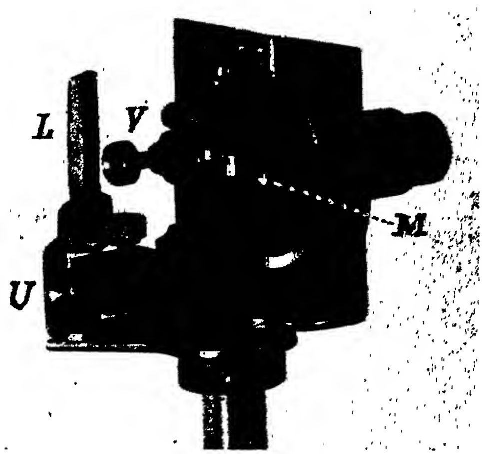


FIG. 9. Diaphragm and vibrator of the phonodeik.

the exposure, is released by a trigger near the ground glass.

The diaphragm and vibrating mirror for the portable phonodeik, *M*, Fig. 9, are of the same design and dimensions as those of the laboratory instrument except as regards the thickness of the diaphragm. Six interchangeable vibrators are provided, having glass diaphragms of different sensitiveness and ruggedness, varying in thickness from 0.085 millimeter to 0.49 millimeter. Each diaphragm is calibrated for its displacement under static pressure applied over the whole surface. Table I gives, in kilograms per square cen-

timeter and in pounds per square inch, the static pressure for four thicknesses of diaphragm used at Sandy Hook Proving Ground, which will produce a displacement of one centimeter of the spot of light on the photographic film.

TABLE I. Displacement Pressures for Glass Diaphragms.

Thickness	*kg per scm*	*lb per sq in*
0.085 mm	0.00016	0.00228
0.18	0.00066	0.00939
0.31	0.00378	0.0526
0.49	0.0117	0.166

For sounds of low intensity, a collecting horn may be used on the front side of the diaphragm, as with the laboratory phonodeik; and for very faint sounds of simple composition a tuned resonator may be applied, as in the "phonometer" of A. G. Webster.[11] For out-of-door use, the sounds are often of such loudness that no horn is required. The opening into the sound-box where the horn would be attached is closed with a stopper; the other side, the "back side," of the diaphragm is wholly exposed and receives the pressure wave. The reversal of sign of the ordinates of the record when the pressure is transferred from one side of the diaphragm to the other side, may be compensated by threading the fiber in the opposite direction around the pulley on the mirror staff.

For the determination of the frequency of the wave, time signals are recorded on the film simultaneously with the wave form by means of a stationary small mirror which is mounted just above the vibrating phonodeik mirror. A tuning fork with electromagnetic drive, operated by means of a dry cell, is mounted on the same base as is the arc lamp, Fig. 8. Attached to the prongs of the fork are two thin

aluminum plates, with holes so arranged that the light from the illuminated pin-hole always falls on the phonodeik mirror whether the fork is in vibration or not. In each aluminum plate is a narrow slit; when the prongs of the fork are in their middle positions, the light from the pin-hole passes through the slits to the fixed mirror and then to the photographic film; when the fork is in vibration this beam of light is interrupted and is recorded as a row of dots parallel to the axis of the wave. A calibration of this fork gives for the interval between successive dots 0.0049299 second, there being 202.84 intervals per second. These time signals appear on all the records made with the portable phonodeik here shown, as in Fig. 10, where the hundredths of seconds have been numbered 1, 2, 3, etc.

When longer records are required for showing progressive changes in the sound wave or for measurements of velocity, the method of a moving film is used. Two special film boxes of larger size are provided, one for long times of exposure with slow-moving film, and one with variable high speed of the film. The slow-speed film box shown in position behind the arc-lamp in Fig. 8, is provided with two reels, each with a capacity for 100 feet of film 2¾ inches wide. The film is reeled from one reel to the other, during exposure, in the manner of a motion picture camera. There is a footage indicator to show the amount of film exposed and also the amount still available. The second film box contains a revolving drum two feet in circumference, driven by the electric motor. The wave form is seen on the ground glass by means of the revolving mirror; the speed of the motor is adjusted to secure a wave form of the desired length. When the trigger is operated, the revolving mirror is depressed out of the light path, so that the light passes directly from the

vibrating mirror to the film. An automatic shutter is arranged so that the exposure corresponds to one revolution of the film drum, whatever the speed of revolution may be.

A photograph of the sounds from a Springfield service-rifle, made with the phonodeik here described, is shown in original size in Fig. 10. The phonodeik was located about 35 feet in front of the gun and 3 feet from the trajectory. The velocity of the projectile was about 2700 feet per sec-

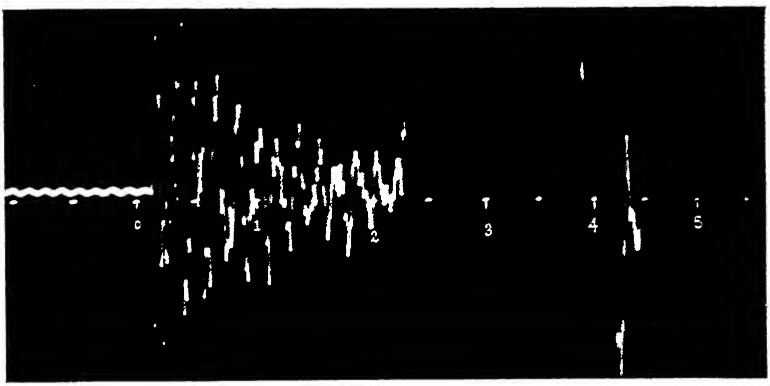


FIG. 10. Phonodeik record of the sounds from a service rifle.

ond. The time-signal interval is about one two-hundredth of a second. The first part of the record, lasting 0.02 second, is the sound from the projectile as it passes the phonodeik; this is followed by the boom-sound from the muzzle of the gun. All of the photographic records of sound waves shown in the chapter relating to the wave form of sounds from large guns were made with the portable phonodeik, using the slow-speed film box, operated by hand.

Corrections for Resonance Effects

For the investigation of complex sound waves, the recording apparatus should (a) respond to all the frequencies of

tone being investigated and to any combination of simple frequencies; (b) it should not introduce any fictitious frequencies; (c) there must be a determinate relation between the response to a sound of any pitch and the intensity of that sound.

It is well known that the response of a diaphragm to waves of various frequencies is not strictly proportional to the amplitude of the wave; the diaphragm has its own natural periods of vibration, and its response to impressed waves of frequencies near its own is exaggerated in degrees depending upon the damping. The collecting horn also greatly modifies waves passing through it, affecting different frequencies in different degrees. Therefore, it follows that the resultant motion of the diaphragm may be quite different from that of the original sound wave in the open air.

It has been shown by actual trial that the phonodeik responds to all frequencies of the audible range up to 12,400 and higher; various combinations of simple tones to ten in number, produced with tuning forks, have been photographically recorded and the records have been analyzed; in each case the analysis shows the presence of all the tones sounded and of no other components. It remains to determine the accuracy with which the response represents the original tones; this requires the investigation of all the factors of resonance, interference, and damping.

The most precise test of the linear response of the phonodeik is given by the record of a Koenig tuning fork, actuated by an electromagnetic driving device. The harmonic analysis of the record shows that 99.5 per cent of the energy of the sound emitted is contained in the fundamental component. The analysis shows no trace of the second harmonic or octave, while the remaining half of one per cent

of the energy is nearly evenly distributed among the next five harmonics.

The influence of the natural periods of vibration of the horn and of the diaphragm, resonance effects, introduce serious disturbances which appear as distortions in the photographic records; these effects must be calibrated and corrections must be applied. The neglect of corrections for the resonance effects which occur in all kinds of vibratory recording apparatus often leads to wholly false conclusions regarding the characteristics of the phenomenon being studied. Detailed accounts of the distortions introduced by resonance, interference, and damping in records made with the phonodeik, and of methods for correcting the analyses for these effects, have been given with full illustrations in "The Science of Musical Sounds," Chapter V.[16] A brief outline only of these effects will be given here.

The actual response of the apparatus is determined by means of a set of ninety-two organ pipes covering a frequency range of nearly eight octaves from 64 to 12,400 vibrations per second by semitone intervals. The pipes are of wood of the stopped diapason type known as "tibia" pipes, especially voiced for simple tone and adjusted to uniform loudness throughout. The pipes are sounded in front of the phonodeik, one at a time, and the resulting amplitudes of vibration are recorded photographically. These amplitudes are plotted on a special chart, as shown by the curve *a*, Fig. 11, which represents the response of an early form of phonodeik. The vertical lines indicate the semitones of the musical scale, as do the strings of a pianoforte, while the little rectangles at the bottom correspond to the keys, covering a range of six octaves from two octaves below middle C to the upper end of the keyboard, a frequency

range from 65 to 4138. The adjustment for uniform loudness is verified by photographing the responses obtained with two or three diaphragms of differing characteristics, as illustrated in Fig. 12. The smooth curve *b* represents the amplitudes for the ideal response of uniform intensity (energy) throughout. The sharp resonance peak *D* is due to the free period of the diaphragm.

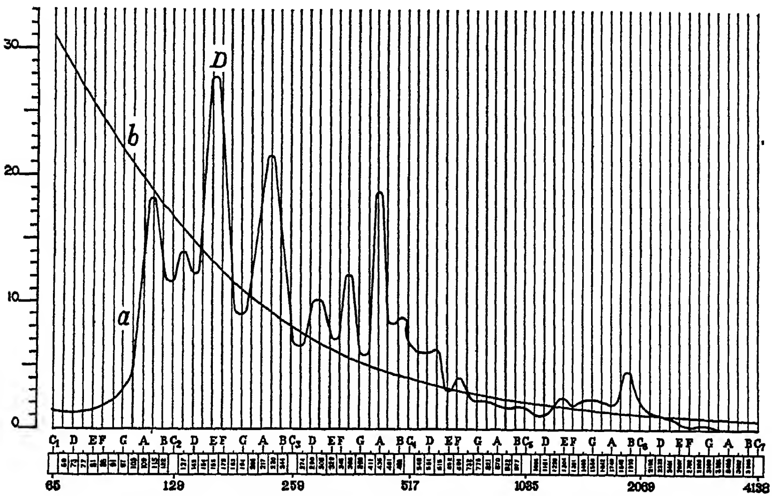


FIG. 11. Ideal and actual response of a phonodeik.

The responses of three glass diaphragms, without a collecting horn, having diameters of 22, 31, and 50 millimeters, respectively, are shown in curves *a, b,* and *c,* Fig. 12. When the pitch of the pipe being sounded is near the natural frequency, or "free period," of the diaphragm, the latter responds easily and moves through a larger amplitude, and the response curve shows a resonance peak. The free period of the largest diaphragm is $D_1 = 366$, curve *c;* the smaller diaphragms have higher free periods of 918 and 1642, re-

spectively. The smaller resonance peaks at higher frequencies represent the natural overtones of the diaphragm.

When a horn is added to the diaphragm, the response is greatly altered. Fig. 13 shows the responses of the same

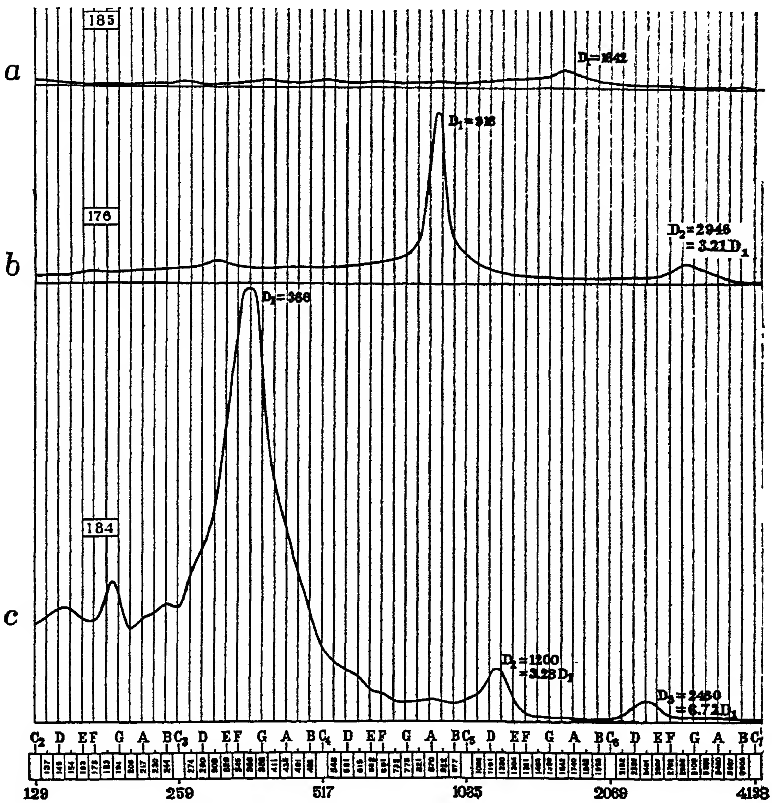


FIG. 12. Resonance peaks for diaphragms of different diameters.

diaphragm when used with three different horns of different lengths. In each curve the resonance peaks corresponding to the fundamental of the horn H_1, the octave H_2, and the other overtones up to the seventh are clearly shown. The resonance peak of the diaphragm is marked D.

A long horn responds to high tones nearly as well as does a short one, while the response to low tones is much greater. A horn should be used of such a length that its fundamental frequency is lower than the lowest tone being investigated.

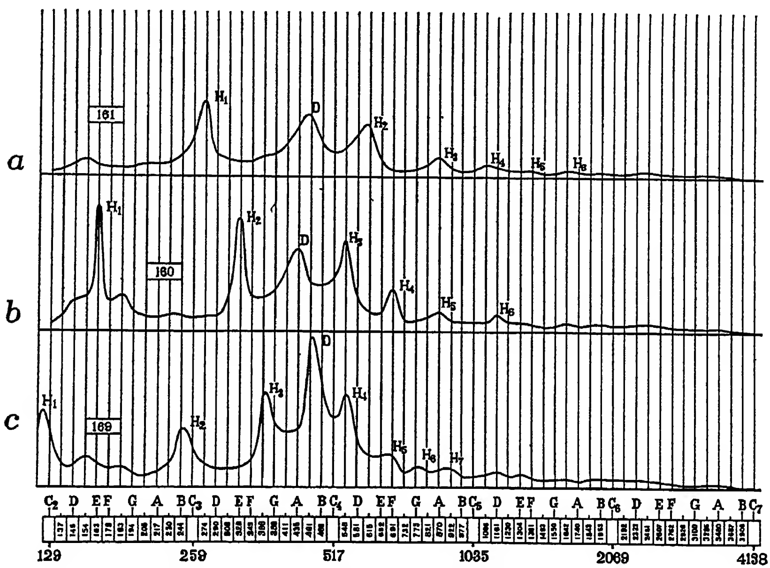


FIG. 13. Resonance peaks for horns of different lengths.

The amount and shape of flare of the horn has a great influence upon the response.

One may wonder, if the horn produces such disturbances as are shown in these illustrations, why is it not dispensed with in scientific research; the horn has been retained because it increases the sensitiveness of the recording apparatus several thousandfold, and because a method has been developed for correcting the distortions introduced by the horn. The details of the method of correction, with numeri-

cal examples, are given in "The Science of Musical Sounds," pages 162-174.[16] The adequacy of this method is shown by Figs. 14 and 15. Fig. 14 shows three records of the *same*

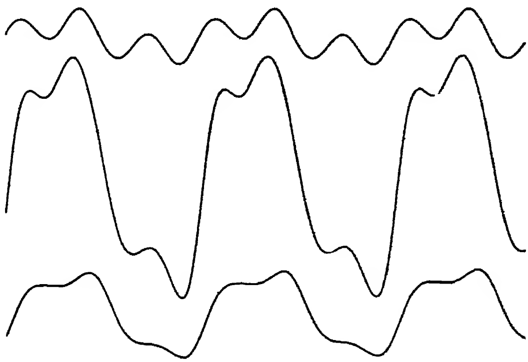


FIG. 14. Three curves for the same tone made under different conditions.

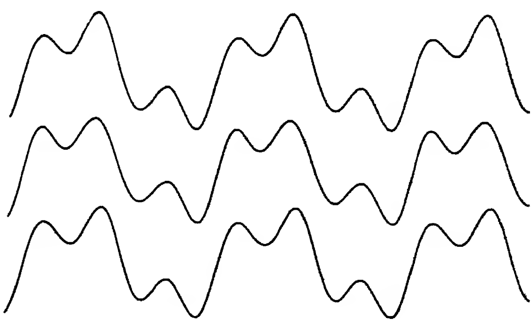


FIG. 15. The three curves of Fig. 14 corrected for resonance distortions.

tone from an organ pipe, made with three different horn-and-diaphragm combinations. The curves were each corrected by the method referred to, giving the three curves shown in Fig. 15. It is reasonable to infer that these curves represent the true shape of the sound wave in the free air, and are suitable for quantitative, comparative studies.

In the definitive study of a musical instrument or voice it is desirable that a large number of tones be photographed, perhaps four per octave, three semitones apart, throughout the whole compass of the instrument; each tone should be sounded in three or more different intensities, as *p*, *mf*, and *f*; and two or more horn-and-diaphragm combinations should be used in the recording apparatus. Any scheme less comprehensive than this will not give an adequate idea of the tone quality of a musical instrument.

Chapter III

THE SHAPES OF SOUND WAVES

Interpreting Phonodeik Records

The phonodeik makes a record of the variations in the pressure of the air at a given point due to the passage of a sound wave. The displacement of the light-spot in the apparatus varies with the intensity of the pressure. The record being made on a moving photographic film, it constitutes a "time graph" of the pressure change, and to the eye it is a graphic representation of the wave form, or it may be described as a photograph of the shape of the wave; such records give much information, of various kinds, of value and interest.

The phonodeik records are useful primarily for harmonic analysis to enable the specification of tone quality; simple inspection of the wave form often will indicate what overtones are present and will give an approximate analysis of the phenomenon which has been recorded.

If a wave consists of alternate half-waves which are exactly of the same shape but are oppositely directed, that is, if the wave is symmetrical with respect to its axis, it can contain only odd-numbered components; if the wave is not symmetrical with respect to its axis, it must contain even-numbered components, and it may consist of both odd and even partials. Sound waves belong to the latter class, no

instance having been observed of a symmetrical sound wave, except that of a tuning fork giving a simple tone of one component only. Electric current waves from an alternating-current generator are usually of the first kind, consisting only of odd-numbered components; an oscillograph record of such a symmetrical wave is shown in Fig. 16.

Often a particular component is prominent and so impresses its effect upon the wave as to produce distinct wavelets or ripples on the main wave form; the order of such a

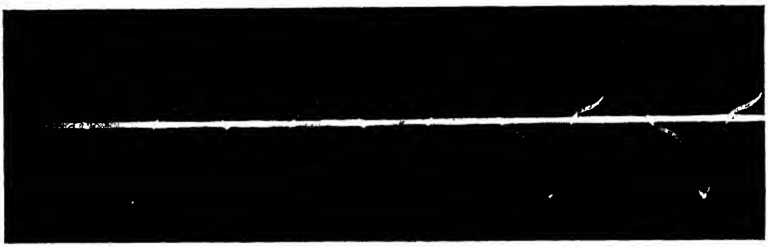


Fig. 16. Symmetrical wave form of an electric alternating-current.

partial is at once determined by merely counting the number of such wavelets occurring in one fundamental wave length.

In some instances the wavelets due to the higher partials are very pronounced in portions of the wave and almost disappear at intermediate parts; this indicates that there are beats between certain partials. Often it is possible to determine, by inspection, which partials are beating, as is described on pages 52 and 54 in connection with the photographs of curves *D*, Plate I, and *G*, Plate II.

The presence of a strong fundamental component is easily recognized. A wave which has a very strongly marked but narrow peak of the fundamental frequency, however, may have a very weak fundamental component. If a con-

siderable number of higher partials have phases which are nearly zero, then once, and *only once,* in each period of the fundamental, these higher components all start their most rapid positive displacements at nearly the same time. This condition produces a sudden and large displacement which is soon counteracted by the reversal of displacement of the components of shorter periods. Curves in which this peculiarity is marked are *H, J, K, M,* and *P,* of Plates II, III and IV.

The amplitude of the wave is related to the energy or loudness of the sound. Loudness of a sound is a comparative statement of the strength of the sensation received by the ear; but it is impossible to state simply the factors which determine loudness. In a first study of the physical characteristics of sounds, attention may be confined to the energy as indicating loudness. The energy in a simple wave varies as the square of the product of amplitude and frequency, and the relative values of these two factors are directly given by the photographic records of the sounds. However, practically all sounds which are studied are complex sounds; and a simple measurement of the amplitude and frequency of the wave is not sufficient for a determination of the energy. It is necessary to analyze the wave into its simple components, to compute the energy due to each component singly, and then to take the sum of these intensities.[1]

The photographs obtained with the phonodeik permit a very convenient and accurate determination of pitch; the time signals are given by a standard tuning fork, recording one hundred flashes per second; it is only necessary to compare the wave length and the time intervals to obtain the frequency. Most of the photographs described in the next

section, and also those in the Frontispiece, show such time signals.

A standard clock with a break-circuit attachment may be made to record signals simultaneously with the sound waves; by counting and measuring, the number of waves per second may be determined with precision. When two sounds are being compared by the method of beats, the exact number (including fractions) of beats per second may be determined by photographing the beats together with the time signals.

The phonodeik permits accurate tuning of all the harmonic ratios; if the spot of light is observed without the revolving mirror, its movements take place in a straight line; two tones sounding simultaneously give a composite wave form, the turning points of which are visible as circles of extra brightness on the line, like beads on a string. When the ratio of the component tones is inexact, there is a constant change of wave form which causes the beads to creep along the line; when the ratio is exact, the wave form is constant and the beads are stationary, signifying perfect tuning.

Photographs of Sound Waves from Voices and Instruments

A selection of typical phonodeik records, with analytical descriptions, is given, illustrating the principle that the factors which produce various tone-colors determine the shape of the wave. Plates I, II, III, IV, and V show records obtained from a variety of sources which produce musical sounds, that is, sounds which have periodic wave forms. Plate VI shows records of non-periodic sounds, or noises.

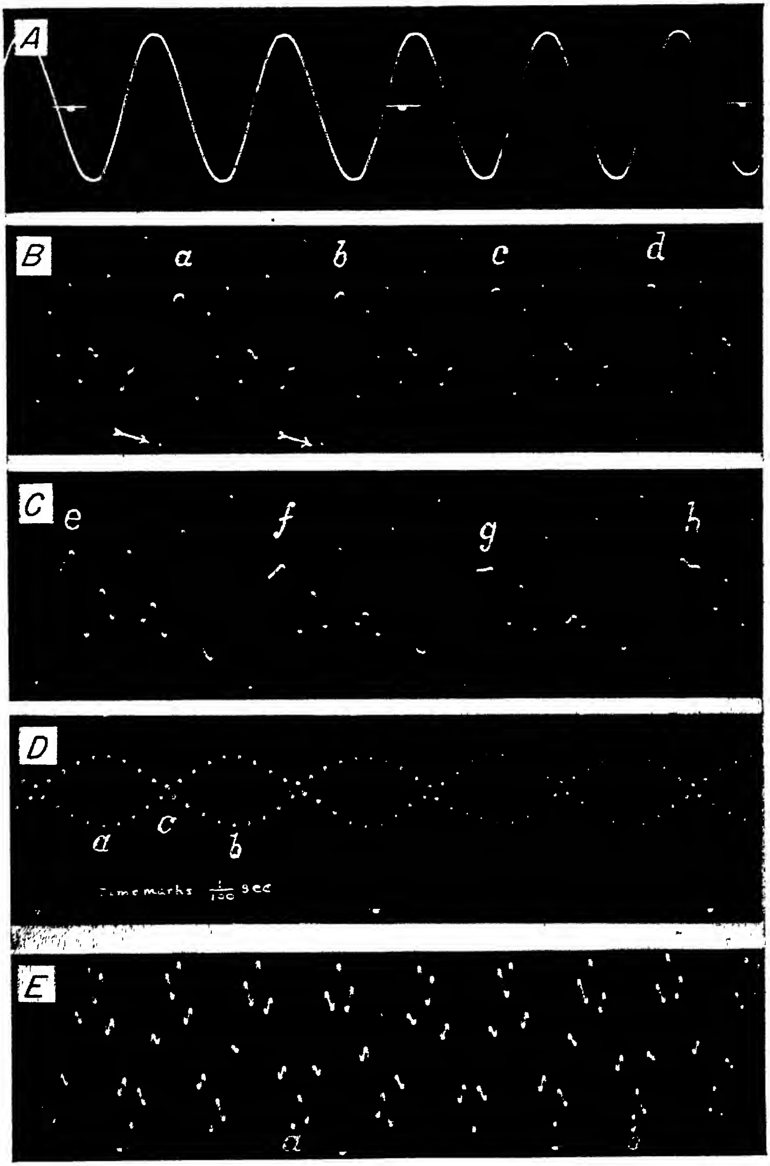
The Frontispiece contains records of complex sounds, vocal and instrumental, of mixed qualities, and recorded at slow speed, thus giving a kind of general outline of the sound.

Curve *A*, Plate I, is a record from a Koenig tuning fork with a resonance box, giving the tone middle C of frequency 256 vibrations per second. It represents the simplest pure tone, produced by a simple harmonic vibration. Curve *B* represents the sound from four forks giving the tones of the common chord, *do, mi, sol, do,* tuned in pure intonation, having 256, 320, 384, and 512 vibrations per second, respectively. The ratios of these frequencies are as 4:5:6:8; that is, the tones are harmonics of a fundamental of frequency 64. The wave form is exactly periodic, repeating itself every 64th of a second. This period is indicated by arrows marked on the record. Curve *C* is the record from four forks tuned to the equally-tempered tones of the common chord, having 256, 322.6, 383.6, and 512 vibrations per second, respectively. The ratios of these frequencies are as 400:504:599:800. The combination of these incommensurable frequencies results in a non-periodic curve, with a progressive change in the wave form. The exactness of tuning in Curve *B* is shown by the constancy of a particular phase relation of higher partials as at *a, b, c,* and *d*. The "out-of-tuneness" of the tones producing Curve *C* is evident by the progressive change in the relative phases of the partials as indicated at *e, f, g,* and *h*.

When two simple tones are sounding simultaneously, in general, beats are produced, equal in number to the difference of the frequencies. Curve *D*, Plate I, is the wave form resulting from the combination of the tones from two tuning forks having frequencies of $C_6 = 2048$ and $D_6 = 2304$, respectively, the ratio of the frequencies being 8:9. If the

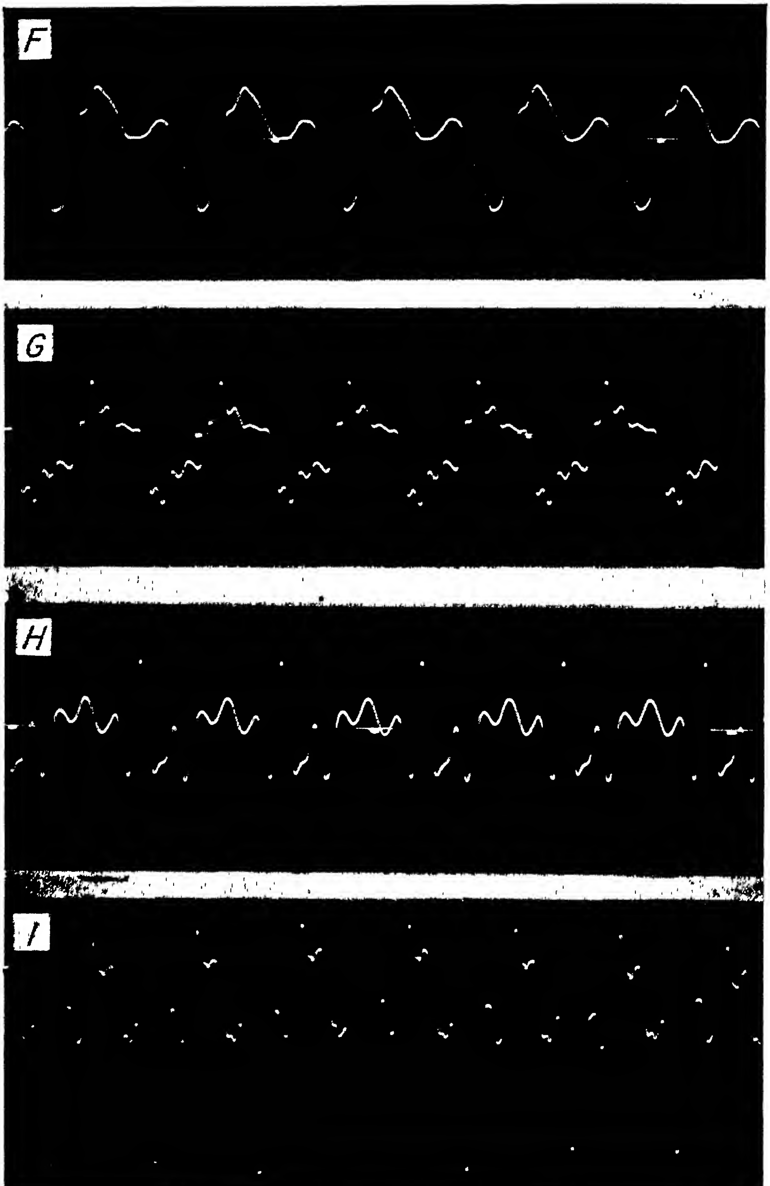
two waves are in like phase at a certain instant, their resultant effect is a wave of large amplitude as at *a*, signifying a loud sound. This condition is repeated at regular intervals along the wave train, as at *b*, which is exactly eight waves of one tone and nine waves of the other from *a*. A point *c*, midway between *a* and *b*, is four waves of one tone and four and one-half waves of the other from *a*, and the two waves neutralize each other, resulting in a minimum of sound. The waxing and waning of sound in this manner, as the result of the combination of two simple tones, constitutes the phenomenon of beats. The number of beats per second is equal to the difference of the frequencies of the generating tones. When the number of fluctuations in the loudness of the sound is less than sixteen per second, the ear distinguishes the separate pulsations, producing the sensation of beating; when the number of pulsations is large, the effect perceived through the ear is that of a continuous simple tone of a frequency equal to the number of beats per second. Such a sensation is called a "beat-tone"; it is often referred to as a difference-tone or a combination-tone. There are 256 beats per second in the instance described, and the ear hears not only the two real fork-tones, $C_6 = 2048$ and $D_6 = 2304$, but also a "third-tone" of pitch $C_3 = 256$. The latter sounds just as real as the other two tones, but it has no physical existence as a tone; there is no vibrating component of motion corresponding to the beat-tone, an analysis of the wave form showing only the two components due to the forks. While beat-tones are purely subjective, yet they have great influence on the tone quality of many instrumental and vocal sounds as perceived by the ear, a fact which has not been adequately investigated in the study of tone color. The physiological and psychological processes

Plate I. PHOTOGRAPHS OF SOUND WAVES.



A. Tuning Fork—simple tone. *B*. Four Tuning Forks—pure chord. *C*. Four Tuning Forks—tempered chord. *D*. Two Tuning Forks—beat tone. *E*. Tuning Fork—clang tone.

PLATE II. PHOTOGRAPHS OF SOUND WAVES.



F. Flute. *G*. Clarinet. *H*. Oboe. *I*. Saxophone.

involved in the sensation of hearing beat-tones have been extensively investigated. The subject still presents aspects requiring further research.[18]

If a tuning fork is struck a sharp blow with a wooden mallet or other hard body, it gives a ringing sound in which the ear distinguishes a high-pitched clang-tone which is a natural overtone of the fork. Curve *E*, Plate I, is a photograph of such a sound, the kinks in the wave form being the record of the overtone. This sound was produced from the same fork as was used for the simple wave shown in curve *A*. Inspection shows that the relation of the small wave to the large one occurring at the point *a* does not recur till the fourth succeeding wave, at *b*; in the four large waves there are twenty-five kinks due to the small one, that is, the frequency of the overtone is about 6.25 times that of the fundamental. Since there is not an integral number of the smaller waves to one of the larger, the partial is inharmonic or out of tune, and hence the sound is clanging or metallic rather than musical.

Plate II shows photographs of the sound waves from various wind instruments. Curve *F* was made with a flute in G, sounding the tone $C_3 = 256$ vibrations per second. The fundamental constitutes the greater part of the tone; the larger kink in the top of the curve corresponds to the octave overtone, while the smaller kinks are due to the double octave or fourth partial tone. The general simplicity and smoothness of the wave indicates that there are no other overtones of appreciable intensity. A sound consisting of a fundamental and the octave and double octave only, wholly lacking in odd-numbered partials, produces the sensation of mellowness and simplicity characteristic of certain tones of the flute.

Curve *G*, Plate II, is the record from a clarinet sounding the tone $C_3 = 256$ vibrations per second. There is a strong fundamental together with at least two higher partials. The two partials beat with each other, once per period, hence they are consecutive in number and one is odd numbered and the other even numbered. Eight kinks are evident, and the stronger partials are either the seventh and eighth, or the eighth and ninth; which, it is difficult to determine from simple inspection; machine analysis, in this case, shows that the stronger partials are the eighth and ninth, while there are traces of the third, fifth, and seventh partials. It is the presence of these relatively loud higher partials that produces the reedy tone quality.

The record from an oboe sounding the tone $C_3 = 256$ vibrations per second is shown in curve *H*, Plate II. The fundamental component is almost wholly lacking; the fourth and fifth partials contain the greater part of the energy of the sound, while there are traces of a series of higher partials indicated by the long and narrow projections in the wave form.

The saxophone record, curve *I*, Plate II, shows a strong fundamental, with both even and odd harmonics, all starting in the same phase. The fourth partial, the double octave, is the strongest overtone, with the fifth and sixth of moderate intensity. Machine analysis shows the full series of overtones of diminishing strength to the fifteenth.

The tone of the French horn is described by Lavignac as "by turns heroic or rustic, savage or exquisitely poetic." The curve *J*, Plate III, is the record of a low tone of the horn sounding $D_1 = 75$ vibrations per second. This tone falls in the group of "poetic" tones; it sounds, as the record looks, rich, smooth and mellow. The analysis of the curve shows

the presence of the entire series of partials up to thirty, with the partials from the second to the sixteenth about equally loud, each yielding about 6.5 per cent of the total energy of the sound. The fundamental has an intensity of four-tenths of one per cent of the total. The records for the tones which may be called "heroic" or "savage," show curves which are jagged and disrupted due to the presence of strong higher partials; this quality of tone is also produced by the trombone.

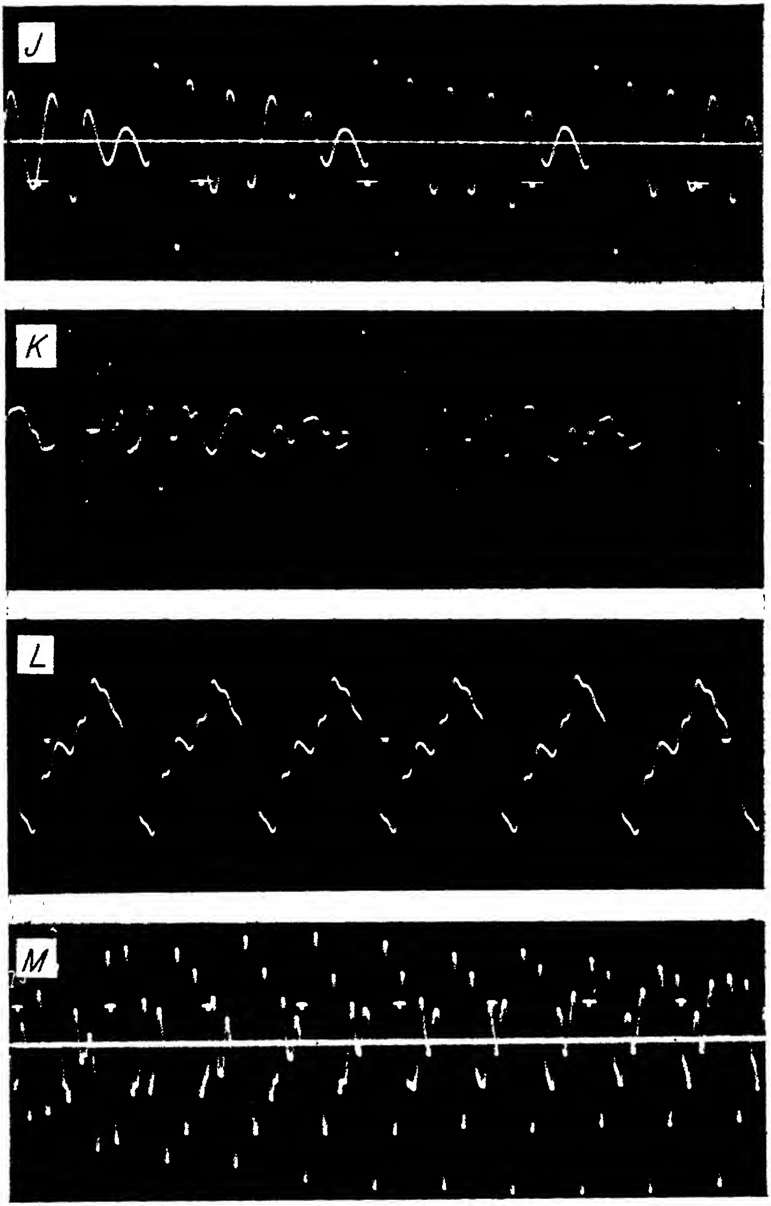
The photograph of the tone of the trombone, *K*, Plate III, gives indication of the vibrant, brassy tone which is characteristic of this instrument. The analysis of this curve shows an entire absence of the fundamental component, and a very weak second partial; the partials from the third to the thirtieth (the end of the analysis) are all present in appreciable intensities. The greatest intensity is in the tenth and eleventh partials, each having 13 per cent of the total energy; the seventeenth partial has 7.4 per cent, the twenty-eighth partial has 5 per cent, and the twenty-ninth and thirtieth partials each have 4 per cent of the total energy. The record of this tone shows a sharply marked peak of the fundamental frequency for the reasons explained on page 49. The listener assigns a pitch to the sound corresponding to the frequency of the fundamental component, though this partial does not exist objectively; the assumed fundamental tone is a subjective effect of the beat-tones produced by the strong upper partials, as described on page 52. The curves *H, J,* and *M*, for the oboe, horn, and piano, respectively, show similar conditions as to the absence of the fundamental and a subjective assignment of pitch.

The effect of the method of generating the tone is often clearly apparent in the photograph of the wave form, as in

the record of a violin tone, *L*, Plate III. When the bow moves uniformly across the string, the string is put into periodic vibration. When a steady state has been established, it is found that the string moves in the direction in which the bow is moving for the greater part of each period; the increasing tension due to the displacement of the string causes the string suddenly to slip and fly backwards until it is again caught by the friction of the bow. When moving with the bow, the friction causes it to move more slowly than when it slips backwards; the slope of one side of the wave is greater than that of the other side. The kinks in the wave form due to the overtones are more conspicuous on the side of the wave which moves slowest; on the rapidly moving side of the wave the kinks are nearly stretched out into a straight line. Helmholtz and others have shown that the string itself partakes of this kind of motion, and the photographic record indicates that these peculiarities are transmitted to the wave in the air.

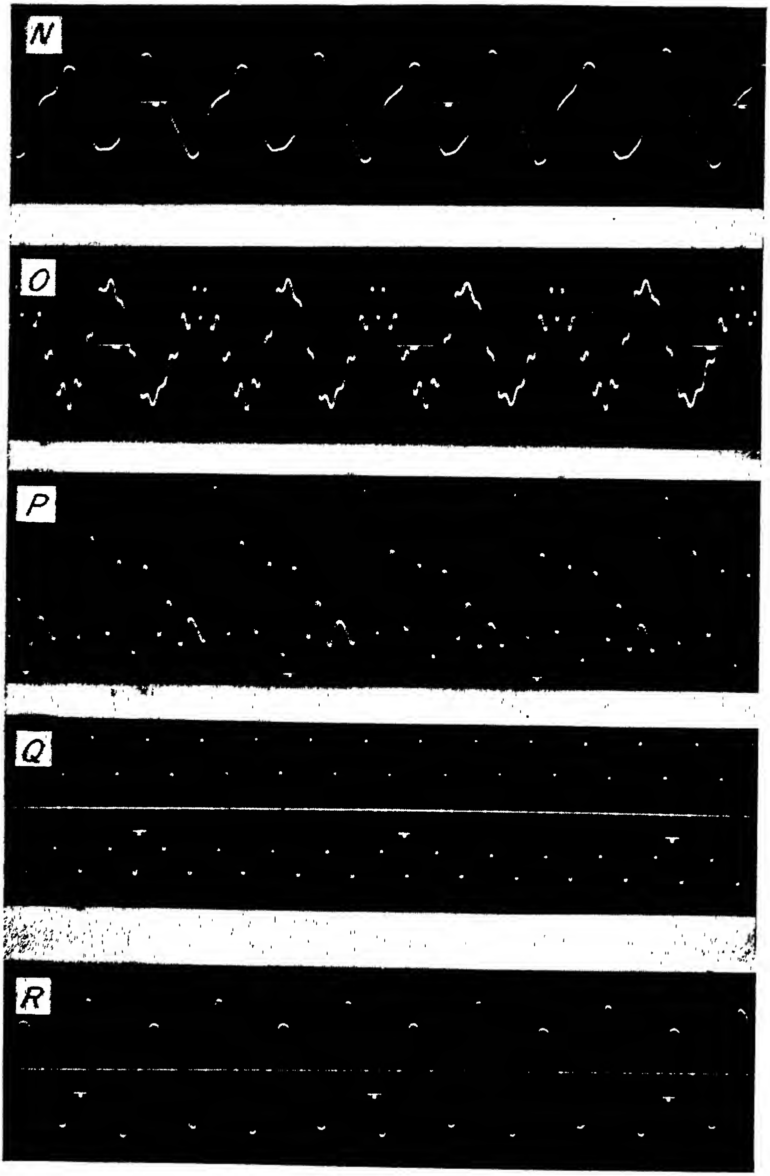
The photograph *M*, Plate III, is the record of a piano tone, pitched nearly an octave below middle C, having 137 vibrations per second. The tone of the piano, in general, does not attain the steady state, and the wave form is only approximately periodic. The string is struck with a felt hammer, which is in contact with the string for a short but appreciable time of a few hundredths of a second; during this time the tone is being developed. After reaching its full strength, the tone immediately begins to diminish in intensity; the various partials are dissipated at different rates and the wave form alters continuously. Moreover, the overtones of a metallic string are not exactly harmonic; there results a continual change in the relative phases of the partials and a progressive change in the wave form from this

PLATE III. PHOTOGRAPHS OF SOUND WAVES.



J. French Horn. *K*. Trombone. *L*. Violin. *M*. Pianoforte.

PLATE IV. PHOTOGRAPHS OF SOUND WAVES.



N. The vowel gl*oo*m. C. D. H. *O*. The vowel b*ee*. C. D. H. *P*. The vowel f*a*ther. D. C. M. *Q*. The vowel f*a*ther. E. E. M. *R*. The vowel n*o*. D. C. M.

cause. The effect upon the sound is to give it a mild metallic or ringing quality. These progressive changes in wave form are clearly shown in the photograph; the developing tone attains its maximum intensity at the time shown in the middle of the record, about five hundredths of a second after its beginning; the sound may continue for several seconds.

The human voice is a wind instrument, the air supply for which is, as in the case of orchestral wind instruments, the human lungs; the generator is the membranous apparatus of the vocal chords, and the resonator consists of the mouth and its associated cavities. There are muscles, nerves, etc., which enable the vocalist to govern the pitch and to change the resonating cavities and to modify other conditions, so that sounds of a wide variety of pitch and quality may be produced, which constitute speech or singing. Speech is characterized by a continual gliding change of pitch and quality of sound, within moderate limits, combined with frequent interruptions and puffs. Singing maintains the sound at a definite pitch for an appreciable time, and uses sounds over a wide range of pitch. Vowels are the definite sounds of speech which can be continuously intoned, separated from the glidings, noises and interruptions by which they are made into words; being continuable sounds, they are considered as the sounds from a musical instrument, and each has a characteristic tone quality by which it is recognized. The tone quality of vowels has been more extensively studied than that of any other group of sounds.

The mouth with its associated vocal cavities is an adjustable resonator; by varying the positions of the jaws, cheeks, tongue, lips, and other parts, this resonator can be tuned to reënforce one or two different frequencies. In singing a particular vowel, the vocal cavities, trained by life-long prac-

tice in speaking and singing, are set unconsciously in the positions that will produce the vowel. At the same time the vocal chords of the larynx are brought to the tension to tune them to the desired pitch. When the air from the lungs passes through the larynx a composite sound is generated consisting of a fundamental of the desired pitch accompanied by a long series, perhaps twenty in number of partials, usually of low intensity. The particular partial or partials in this series which are most nearly in unison with the natural frequencies of the vocal cavities, are greatly strengthened by resonance, and the resultant effect is the sound which the ear identifies as the specified vowel sung at the designated pitch.

If, while the mouth cavity is maintained unchanged in position, the vocal chords are set successively to different pitches and the voice is produced, then one definite vowel, the same throughout, is recognized as being sung at different pitches. In this case the region of resonance is constant, though the pitch of the fundamental may vary, as may also the pitch and order of the particular partials which fall within the region of resonance.

If, on the other hand, while the vocal chords are maintained at a constant pitch, the vocal cavities are altered so as to vary the resonance frequencies, then different vowels will be enunciated, all at the same pitch.

It follows from the principles stated that each particular vowel is not characterized by a series of partials of fixed relative intensity, that is, it does not have a particular wave form; rather, it is characterized by a fixed region, or regions, of resonance or reënforcement. The greater part of the energy or intensity of the voice sound is in the partial or partials which fall within certain frequency limits, no mat-

ter at what pitch the vowel is uttered, or by what quality of voice. The variations in understandable speech and song are so great that we are accustomed to accept as the same vowel, sounds which vary within fairly wide limits.

Five photographs of vowel sounds by different voices have been selected to illustrate the theory of vowels; these are reproduced in Plate IV. Curve *N* is the vowel *oo* in the word gl*oo*m, intoned by C. D. H., a baritone voice, on the pitch $F_2 = 170$. By far the greater part of the energy of the vibration, and of the loudness of the sound, is contained in the second partial, there being just enough of the fundamental to give the impression of the pitch; the other weaker partials combine to produce the tone quality in general of this particular voice. The second partial of frequency 340, having about 75 per cent of the energy of sound, determines what vowel is uttered, gl*oo*m in this instance.

The curve *O*, Plate IV, represents the vowel long *e* as in the word b*ee*, intoned by the same voice, C. D. H., as made the record *N*. The analysis shows that the fifteenth partial, represented by the conspicuous kinks, which has a frequency of about 2500 vibrations per second, contains a large part of the energy of the sound, 35 per cent, while the second partial is equally prominent. A direct comparison of the two records indicates that the vowel gl*oo*m is transformed into the vowel b*ee*, by a very slight adjustment of the vocal cavities so as to add a new strong characteristic resonance of high frequency.

Analysis shows that the vowel *a* as in f*a*ther is characterized by strong resonance, the frequency of which may vary from 900 to 1100 vibrations per second. The records *P* and *Q*, Plate IV, are photographs of this vowel sound intoned by a baritone voice, D. C. M., and by a contralto voice,

E. E. M., respectively. The record *P* has a fundamental frequency of $F_2 = 172$, and the sixth partial of frequency 1032 contains 80 per cent of the energy of the sound. The record *Q* has a fundamental frequency of $B_3 = 487$, and the second partial of frequency 974 contains 96 per cent of the energy of the sound.

The record *R*, Plate IV, is a photograph of the vowel in the word n*o*, intoned by D. C. M. at the pitch $A_2 = 226$. This curve is somewhat like curve *N* in form, and also has the greater part of its energy, 69 per cent in this instance, in the second partial having a frequency of 452. The pitch of the dominating partial, 452 vibrations per second, determines that this vowel is n*o*, in contrast with the vowel gl*oo*m of record *N*, the dominant partial of which has a frequency of 340.

Records *P*, *Q*, and *R* illustrate the theory that vowel quality depends upon the frequency region of greatest resonance, and that it does not depend upon the order of the prominent partials. Curves *P* and *Q* represent the same vowel, while the wave forms are unlike; in curve *P* the sixth partial predominates and in curve *Q* the second partial is the strongest; the frequencies of these dominant partials, $1032 = C_5$ and $974 = B_3$, are only a semitone apart. The curves *Q* and *R* are almost identical in form, the second partial of each being the dominant component, but they represent different vowels. The frequency of the second partial of *Q* has the frequency $B_3 = 974$, while the second partial of *R* has the frequency $A_3 = 452$.

An analysis of the vowel in the word m*a*t shows the presence of every partial from the fundamental to the twentieth overtone, inclusive; in another analysis of the same vowel, there are eighteen partials, the highest being the twenty-

fourth overtone. A more extended account of the analysis of vowels, of their synthesis, and of the combination of vowels with other sounds to form words, is given in Chapters VII and VIII of "The Science of Musical Sounds." [1]

Photographs of several musical sounds of special interest are shown in Plate V. Curve *S* is the sound of the fog horn, located at Father Point on the St. Lawrence River, as photographed at a point 860 feet from the horn. Two other photographs of the same sound are shown in Fig. 64 of Part II, one having been taken at a distance of two miles from the horn.

In discussions of harmonic analysis it has been stated that a profile of the human face may be analyzed into a series of simple harmonic terms, each of which corresponds to a simple musical tone;[1] conversely, the wave form of the sound resulting from the simultaneous sounding of a specified series of simple tones should represent the human face. A brief search discovered the phonodeik record of the sounds of a French horn shown in curve *T*, Plate V, the tone being $F_2 = 174$ vibrations per second, played *p*, *mf*, and *f*. When a single wave length of the lower curve is turned with its axis in a vertical direction, it appears as shown at the right end of the picturė; perhaps it suggests a human face.

The record *U*, Plate V, is a photograph of a saxophone tone, not unlike the record *I*, Plate II, in general character; the difference is largely due to a change in the relative phases of the partials. This curve and several others were once exhibited in a lecture before a venerable scientific society and were referred to in the morning newspaper in these words: "The tone of a saxophone looked like a three-jawed crocodile, a piano tone appeared to be a bouquet, and the "Sextette from Lucia" resembled a million-piece kaleido-

scope." These features had not before been noticed. The end portion of this chart shows a portion of the wave turned to a vertical position.

The tone quality of the violin, and its wave form, remain constant so long as the bowing is constant in pressure, speed, and direction. The direction of bowing may be skillfully reversed without appreciable change in tone quality. Curve *V*, Plate V, is a photograph of the wave when a change is made from up to down bowing. The wave form is symmetrically turned over with every change in the direction of the bowing; the disturbance caused by the change consists of an instant of silence, preceded and followed by a slight confusion, the whole lasting only a fortieth of a second. Analytically, the turning over of the wave form signifies that the phases of all the partial tones are reversed; since the ear fails to detect any change in tone quality due to the reversal of phases, this record supports the principle that tone quality is independent of phase relations.

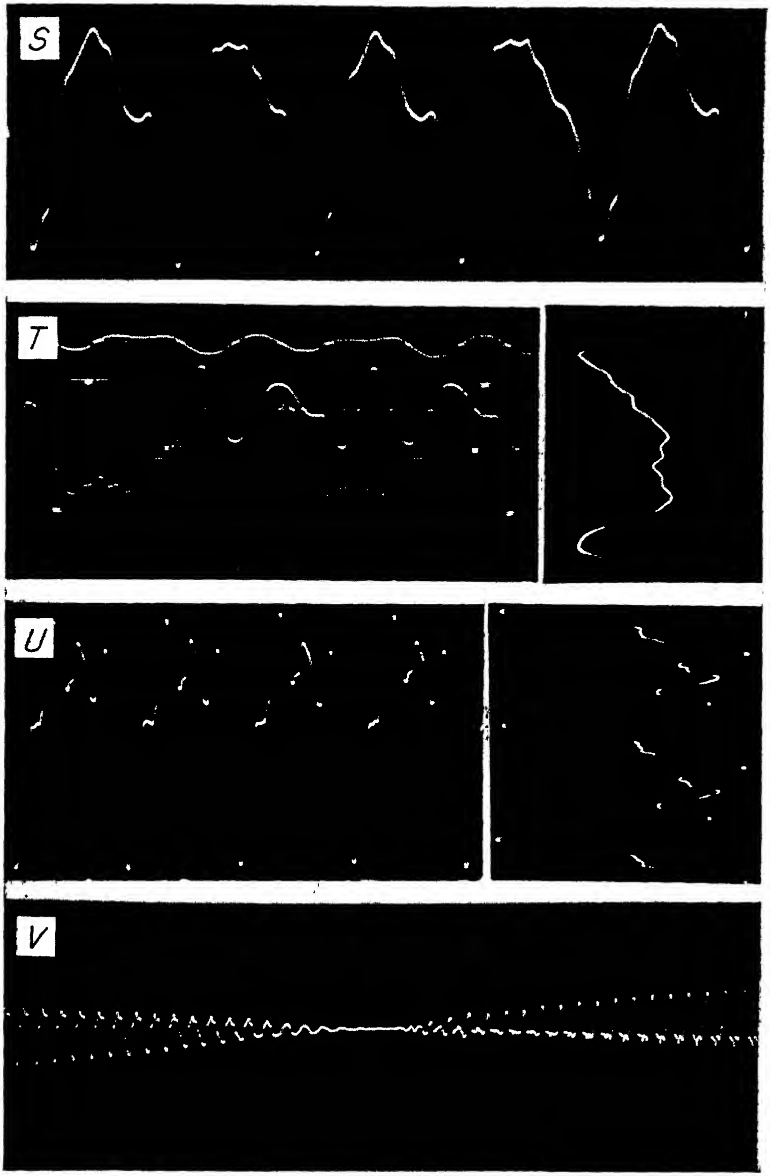
Plate VI shows records of several sounds which produce continually changing and non-periodic wave forms. Usually such non-periodic sounds are classed as un-musical sounds or noises, though sometimes the sound consists of partials which are strictly harmonic as to frequency but have varying amplitudes which causes the change in wave form. Often there is no apparent wave length in the curve. Any portion of such a curve may be analyzed by the Fourier harmonic method, and the resulting equation will completely represent the curve as to *form,* within the limits analyzed, *but not beyond these limits.* The separate terms of the Fourier series, in the case of non-periodic curves, may not correspond to anything that has a separate physical significance. There is no general method for analyzing non-

periodic curves, that is, for curves containing incommensurable (inharmonic) or variable components; such a method would be very useful.

Curve *W*, Plate VI, shows the record of the sound from an organ pipe with a strong fundamental component, the periodicity of which is evident. There are several strong overtones which are quite out-of-tune, producing a tone which is very unmusical to the ear; these inharmonic partials give a jagged, unsymmetrical, non-periodic record for the composite tone. This quality had been purposely produced by loading the wall of the pipe in an unsymmetrical manner. An analysis of any portion of this curve could be made; it would result in an equation of a large number, perhaps an infinite number, of terms, which would be artificial as to physical significance. The real sound is undoubtedly a composite of a small number of partials whose frequencies are incommensurable and are therefore indeterminate.

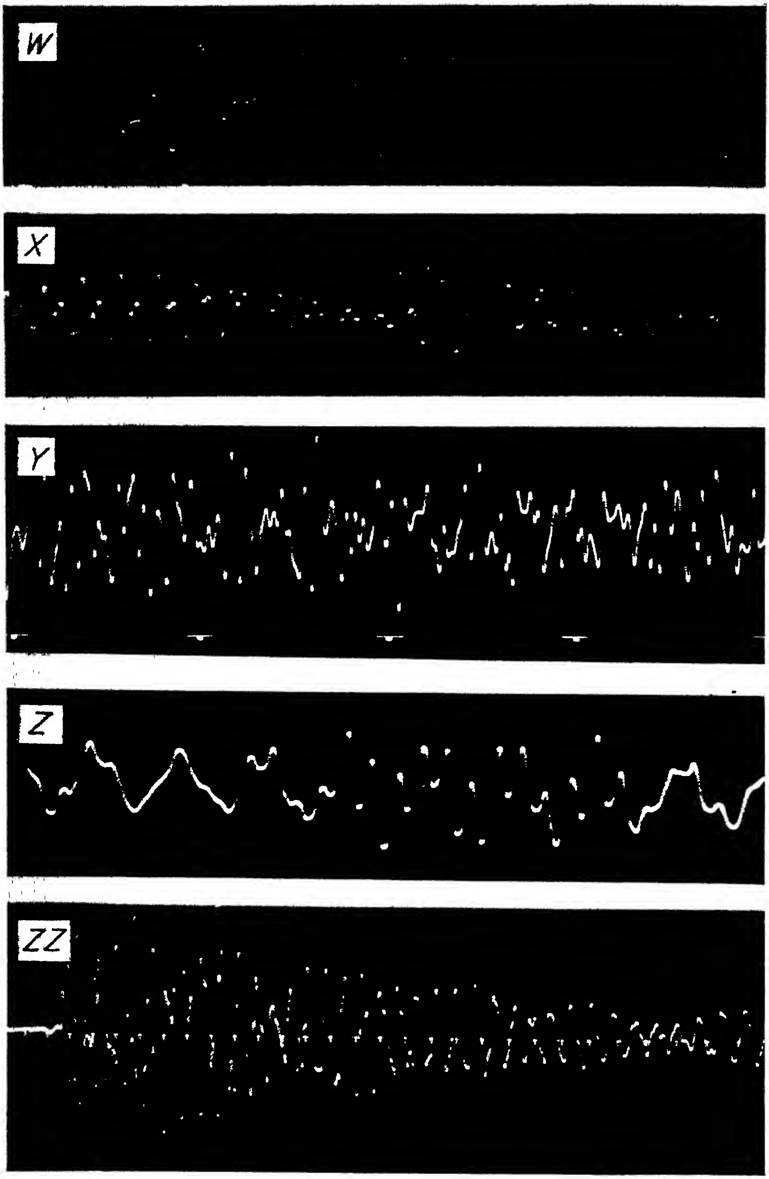
In speech the vowel sounds are connected together by means of transition sounds, or are separated by the fricative rustlings of the breath, or by interruptions; these effects are, in general, the consonants of speech, and are noises represented by non-periodic wave forms. If the syllable *mow* is repeated *mow—mow—mow*, the *m* sound between two vowel sounds produces a wave form shown in the record *X*, Plate VI. This non-periodic sound quickly changes into the simple periodic sound of the vowel *o*, such as is shown in the record *R*, Plate IV.

The music of a band or an orchestra is made up of a combination of sounds each of which may be periodic; and though all the sources may be "in tune" with each other, yet because the components are so numerous and are continually varying in pitch, the resultant wave form is non-



S. Fog Horn. *T*. French Horn. Profile. *U*. Saxophone. *V*. Violin. Reversal of Bowing.

Plate VI. PHOTOGRAPHS OF SOUND WAVES.



W. Double-walled Organ Pipe. *X*. The Consonant m-m-o — m-m-o. *Y*. Music of a Brass Band. *Z*. Clang of a Bell. *ZZ*. From a Sky Rocket.

film is from three to five feet per second, about a tenth of the speed of the film for the records which have just been described. While such records contain much useful information, they are not suitable for harmonic analysis.

The photograph *A*, in the Frontispiece, shows part of the word "laboratory" in normal speech by D. C. M. The entire word has a duration of 1.2 seconds, the record for 0.8 second only being shown. The vowels are represented by the wider parts of the curve; the consonants *b* and *t* consist of almost complete interruptions of sound, each lasting about 0.08 second. The development of the initial *l* sound and its transition into the vowel *a*, and the continual modulation of the vowel sounds, are interesting features of the record.

The exact form of the record depends not only upon the words spoken, but also quite as much upon the peculiarities of the individual voice and upon the resonance characteristics of the recording apparatus. The incidental variations and the extensive vocabulary of language would produce an enormously extended set of records, yet it is possible to learn to "read" the sound-wave records of spoken words; such records constitute a system of phonetic writing, but the system is neither "shorthand" nor "simplified spelling."

Such records are, doubtless, capable of being transformed into corresponding movements of the air, and thus the original sound may be reproduced after the manner of the talking machine.

An illustration of a sound of extreme complexity, and one which in the usual sense is non-periodic, and which nevertheless gives pleasurable sensations, is shown in photograph *B* of the Frontispiece. This is the record of the sound from a baritone singing voice with orchestral accompaniment, as

reproduced by a talking machine. The selection is the song "Thursday," sung by David Bispham; it shows the word *"river's"* and the beginning of the word *"brim."* The duration of the part of the song shown is 0.8 second; on the scale of the original photograph which is five inches wide, the length of the film required to record the entire selection would be about 600 feet.

The sounds of bells are very complex, but usually there are five partials of prominence. The first, third, and fifth of these partials are, roughly, successive octaves, with the third and fourth partials forming, very roughly, the common chord within the octave interval between the second and fifth partials. A bell of a famous make is described in Barton's "Text-book on Sound"; assuming the fifth partial as a reference, the first partial is nearly a semitone sharp, the second partial is six vibrations per second sharp, the third partial is four vibrations per second sharp, and the fourth partial is three-quarters of a semitone sharp. Barton says: "To anyone at all familiar with the rules of harmony it might appear incredible that such tones as these five could be heard together with pleasure. But it must be remembered that each tone of the bell is itself a simple partial." The record *C*, of the Frontispiece, is the photograph of the sound of a large hand bell. The sudden increases in the amplitude of the wave are due to the striking of the bell by the hammer; the complete absence of periodicity is evident. The presence of pronounced beats, at the rate of about eighty per second, is shown in the wider parts of the curve; these beats come and go, and tend to produce the wavering sound of the ringing bell.

Chapter IV

ELECTRIC-SPARK PHOTOGRAPHY OF SOUND WAVES

Methods of Electric-Spark Photography

Spark photography as applied to the study of actual sound waves in air, and in photographing rapidly moving bodies such as bullets in flight, had its origin in the "Schlieren-methode," or the method of striae, first proposed by A. Toepler in a paper published in Bonn in 1864, entitled: "Beobachtungen nach einer neuen optischen Methode"; it was further described, as applied to microscopic and stroboscopic objects in *Poggendorff's Annalen der Physik* in 1866.[19] This method makes visible those portions of a transparent medium whose refractive indices differ slightly from that of the surrounding medium; it is based upon the same principles as is the earlier Foucault "shadow test" for showing imperfections in lenses due to striae or varying index of refraction of the glass, or for showing defects in the surface of a lens or mirror.[20]

As arranged by Toepler, the principal piece of apparatus is a field lens of good quality, large diameter and long focus; the objective lens of a telescope four inches or more in diameter with a focal length of several feet is suitable. Light from a source of small dimensions, such as a gas lamp, is brought to a conjugate focus at a distance of perhaps fifteen

feet from the lens. If the eye is placed near this focal point, the lens will be seen uniformly illuminated. A small knife-edge screen is now brought from one side just to cut off all the light which passes regularly through the focal point. If, however, there are striae in the lens or in the air near the lens, the abnormal refraction will cause some of the light to pass above or below the focal point and the striae will appear luminous on a dark field. The observations may be made more conveniently by means of an ordinary reading telescope.

In 1867 Toepler described a greatly improved technique in which is first introduced the use of the electric spark from the discharge of a Leyden jar or other electric condenser, for instantaneous illumination of the field in which there may be objects in motion. The method for making sound waves directly visible by means of two electric sparks is described. The sound produced by an electric spark consists of a single wave, or sound pulse, made up of one condensation and one rarefaction, and the sound is relatively loud, that is, the change in density of the air is considerable; the wave length is very short, two millimeters or less. The wave is propagated spherically through the air at the normal velocity of about eleven hundred feet a second. When the medium through which the sound wave is passing is illuminated by the flash from a second electric spark, produced a small fraction of a second later, the striae of the sound wave are made directly visible. Toepler shows drawings of the progress of a sound wave in air, including the reflection of waves when they strike a solid surface.

About 1880, Ernst Mach photographed the sound waves produced by the electric spark, a camera being substituted for the observing telescope of Toepler's *Schlierenmethode.*[21]

A disadvantage of the method is the small size of the photographic image of the field lens, which is usually only a few millimeters in diameter. Ernst Mach and P. Salcher, in 1884, observed a bullet in flight by means of the electric-spark illumination, and in 1887 they succeeded in making photographs of the condensations and rarefactions of the air produced by the passage of the bullet.[22] The trigger in Mach's method, which sets off the photographing spark, consists in firing the bullet through a secondary trigger gap; the presence of the bullet in this gap reduces the resistance of the circuit so that the potential of the charged condenser causes the spark to pass. This trigger has the disadvantage that the wires of the secondary gap show in the photograph, and also the flight of the bullet may be interfered with.

L. Mach, a son of Ernst Mach, continuing his father's experiments in 1893, improved the apparatus for photographing bullets in flight, though it was still based upon the method of Toepler.[23] He substituted a large concave mirror for the lens of the earlier method, thus obtaining a larger field and a better illumination. He improved the trigger, using an arrangement whereby the wave of condensation produced by the bullet blows the flame of a candle or a Bunsen burner into the trigger gap, causing the discharge of the condenser. The photograph is free of wires or other disturbing details.

In 1880 V. Dvorak introduced the direct shadow method, a simple "refractometric" method, greatly simplifying the process of photographing the sound waves in air.[24] The large field lens, the camera, and the knife-edge screen are dispensed with. The sound-producing spark is near an uncovered photographic plate in a dark room or box; a suitable

shield is arranged, which prevents the light of this spark from falling on the plate, while at the same time the sound wave passes over the plate. The second illuminating spark is at a distance so that it projects the refractometric shadow of the sound wave on the plate where it is recorded. Such a record is a projection of the object from the point source of light, and the image is slightly larger than full size of the object.

In 1893, C. Vernon Boys greatly improved and simplified the technique for photographing bullets in flight; he used the direct projection method of Dvorak, and the trigger device of Ernst Mach.[25] The bullet is fired parallel to and close to the uncovered plate; at the proper time the spark is released and the image of the bullet itself, as well as that of the accompanying air disturbances, is photographically recorded. Boys obtained photographs of a projectile at the moment when it pierces a glass plate; he obtained pictures of the discharge of small shot from a shot-gun, leading to a study of the effect of the choke-bore; he investigated the phenomena of rotation and of tumbling of the projectile from a rifle.

In 1899 R. W. Wood still further simplified the technique of the *Schlierenmethode,* using the two sparks for the study of waves in air.[26] He devised an improved spark-gap for the illuminator, made of magnesium, which is of greater light intensity and at the same time more nearly approximates a point source. Wood produced an extended series of photographs exhibiting the propagation of waves and the progressive changes as they occur in various phenomena of physical optics. These illustrate reflection, refraction, diffraction, secondary wavelets, the production of cusp-waves, and many other effects. The comparatively simple appara-

tus required for these demonstrations is fully described in Wood's *Physical Optics*.

In 1912 the direct projection, or shadow method of photographing the sound waves produced by the electric spark, was further developed by Arthur L. Foley and H. W. Souder.[27] They designed a complete, self-contained apparatus with facilities for the control of the various operations; it contains many improvements in details and is very practicable and certain in its operation. The method for the critical control of the time interval between the sound-producing spark and the spark that makes the photographic record, by adjusting the electric constants of the condenser circuits, which was first recognized by Ernst Mach, is fully developed in Foley's apparatus. A complete description of the equipment is given in *The Physical Review* for November, 1912. Foley later used this apparatus for investigating the speed of sound in tubes and for the determination of the speed of the sound waves; he studied the changes in the wave front and in the energy of the sound wave as it propagated through straight and curved tubes and through megaphones or conical horns.

Wallace C. Sabine, in 1913, adapted the two-spark, direct-projection method as developed by Toepler, Mach, Dvorak, Wood, and by Foley and Souder, to the study of the propagation of sound waves in an auditorium.[27] This method enables the architect to make a critical analysis, in advance of construction, of the proposed design for an auditorium. A small cross-sectional model of the auditorium is prepared, commonly being made of plaster; this model is so placed in the photographic apparatus that the sound spark occupies a position corresponding to a speaker on the stage. When the sound spark is produced, the resulting waves pro-

ceed on their journey through the auditorium and are photographed at any desired time. The relation of the wave length of the spark wave to the dimensions of the model is about the same as that of a voice wave to the dimensions of the real auditorium, so that a comparison of effects is justified. Such model photographs show the effects on the sound wave of the shape and volume of the room and of the kinds of material of which the walls are constructed.

In Sabine's arrangement, the sound spark-gap and the illuminating spark-gap are placed in separate electric circuits, and each circuit is provided with an independent condenser. In each circuit is a supplementary trigger gap; a rifle is so adjusted that its projectile will pass through the two trigger gaps in succession, first setting off the sound spark and then the light spark. The time interval between the two sparks is very definitely controlled by adjusting the distance between the two trigger gaps. Sabine also devised a potentiometer and automatic switch connected with the high-potential circuit; when the condenser is charged to the desired potential, the static charging machine is automatically disconnected, securing certainty and constancy in the operation of the illuminating spark.

Carl Cranz, in his "Lehrbuch der Ballistik," Band III, pages 257-367, gives a very comprehensive survey of "Ballistische Photographie," together with details of his own researches; this section is illustrated with fifty diagrams and sixty photographs. The pictures of bullets in flight with the accompanying air disturbances are probably the most beautiful that have yet been produced. There is an annotated bibliography with references to more than a hundred papers relating to this particular subject.[28]

Photographs of Bullets in Flight

While the author was engaged, at Sandy Hook Proving Ground, in 1919, on the experiments with the phonodeik relating to sounds from large guns, described in Chapter V, it was decided to supplement the work with experiments on the air disturbances produced by the bullets from the Army service rifle. For this purpose a complete equipment for spark photography by three different methods was installed in the Physical Laboratory of Case School of Applied Science. Apparatus was already in place for making observations by the Toepler *Schlierenmethode* as described by Wood. The method adopted for the bullet photography is substantially that of C. Vernon Boys, with one important modification; a mechanical trigger for the illuminating spark was devised, resulting in a relatively long time lag and giving a large field of view free from wires, spark gaps, etc. For the study of wave propagation in models a complete camera was provided according to the designs of Foley and Souder and of Wallace C. Sabine.

The author's research assistant, Mr. Ralph F. Hovey, devoted his whole time to these experiments for more than a year. In 1920 Mr. Floyd A. Firestone and Mr. Philip P. Quayle, then junior students in Case School of Applied Science, devoted their laboratory periods to the bullet photography, the results of which were presented in a joint-authorship paper to the American Physical Society at the Washington meeting, in April, 1920.[29] Mr. Quayle continued his connection with this work in his senior year, making it the subject of his graduation thesis in May, 1921. This thesis was published, perhaps without adequate acknowledgment, in the Journal of the Franklin Institute in

May, 1922. Mr. Quayle later did experimental work at the Bureau of Standards on the application of spark photography to ballistics, the results of which are given in "Scientific Papers of the Bureau of Standards," No. 508, issued in June, 1925.

As a result of the report to the American Physical Society in April, 1920, further experiments on projectiles were undertaken at the Case laboratory with the coöperation of the Ordnance Department of the Army. At this time, Dr. Harvey L. Curtis, of the Bureau of Standards, suggested that the sound wave from the projectile, rather than the projectile itself, can be made to operate the trigger for discharging the condenser, by means of a "rupteur" of the type used in France in connection with the Joly chronograph for determining the velocity of a projectile. The *rupteur* is a diaphragm device; a delicate lever pivoted at one end and insulated, normally rests against the diaphragm, closing an electric circuit through a magnetic switch. When a sound wave, such as that from a bullet, a handclap, or the voice, strikes the diaphragm, the vibrations cause the lever to swing away from the contact, momentarily opening the circuit.

The new apparatus for the experiments with service rifles was set up in the attic of the laboratory, Fig. 17, where there was a clear range of one hundred and thirty feet. A cabinet, about six by eight feet in size, shown at the left, constitutes the camera; it contains the photographic plate, the condensers and spark gap and control apparatus. A large motor-driven static-machine, located beyond the cabinet, is used to charge the electric condenser. The rifle is rigidly mounted on a table, shown at the right, which may slide on a track to take up the recoil of the gun. The rifle is

aimed so that the trajectory passes parallel to and near the photographic plate; the projectile enters and leaves the cabinet through two "windows" covered with black paper, and is received in a box of sand sixteen inches thick, which is near the end brick-wall. The cabinet is arranged so that

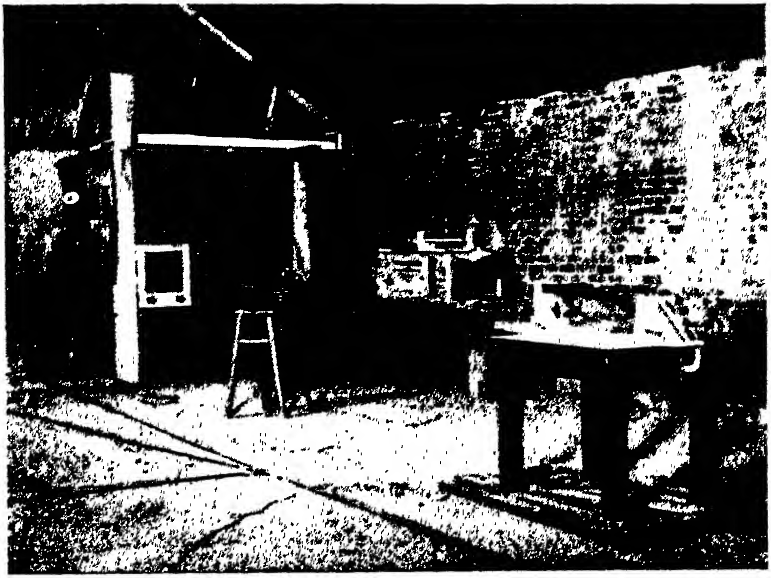


FIG. 17. Laboratory for photographing bullets in flight.

the photographing spark usually projects the image of the bullet in a horizontal direction; the spark may be placed on the top of the cabinet to project the image vertically downwards on the plate. The interrupter is on the iron tripod in the left center of the view. The box in the center background is an early form of camera for spark photography with models. Numerous novel devices and improvements in details were embodied in the equipment, facilitating the operations and resulting in better photographs.

A new form of switch was devised, which brings a piece of wire between the terminals of a long secondary spark gap by means of a pivoted lever operated by a spring. The switch is set by pulling the free end of the lever out of the gap, where it is held by a delicate trigger connected with a relay in the interrupter circuit. When the latter circuit is opened by the head wave of the bullet, the lever is released and the wire passes through the trigger gap, discharging the condenser through the light gap. The moving parts are of aluminum, and the tension of the spring is adjustable. This type of switch has proved to be very constant in action; the trigger gap consists of two portions, one at each end of the wire, and its action is very rapid permitting the use of higher potentials in the condenser.

The spark for making the photographic record is produced between magnesium points as described by Foley; the gap used was about 12 millimeters long, and was so placed that it was directed end-on to the photographic plate.

An important piece of subsidiary apparatus which increases the certainty and convenience of operation, patterned after the device of Wallace C. Sabine, consists of a potentiometer and switch connected with the high-potential circuit of the spark condensers. It performs three functions: when the potential of the charged condenser reaches the desired maximum, the potentiometer operates a switch which disconnects the static charging-machine; the static machine is short-circuited; a subsidiary circuit is closed which lights a signal lamp, indicating to the operator of the gun that all is in readiness. For certain experiments, instead of lighting a signal, the switch may actuate a mechanical device for firing the gun.

In general, such a circuit as that of the light spark will

be oscillatory, resulting in multiple images when discharge occurs. However, by proper adjustments of the capacitance, inductance, and resistance of the circuit, it can be made to pass from the oscillatory condition through the critically damped to the highly damped state; when the critically damped adjustment is secured, the discharge is confined for the most part to a single pulse, giving a sharp image of the projectile. In practice this condition usually can be attained simply by varying a non-inductive resistance in the circuit, determining the proper setting by trial. By measurement of the photographic image it is found that the effective time of exposure in the pictures here shown is less than one two-millionth of a second, and sometimes is as short as one five-millionth of a second; Cranz has obtained exposures as short as one ten-millionth of a second.

The location of the diaphragm interrupter in relation to the trajectory and the photographic plate requires the most critical adjustment. The interval between the time when the head wave from the projectile strikes the diaphragm till the spark is discharged is nearly constant depending upon the mechanical devices only; in this apparatus this interval is about 0.0055 second. In this time the projectile must travel very exactly from its position when the head wave operates the interrupter to its position in line with the spark and the photographic plate. The speed of a bullet varies greatly with the type of projectile and also for different specimens of the same type. A projectile having a velocity of 2700 feet per second moves about 15 feet in 0.0055 second. For photographing such a projectile the interrupter would be set 15 feet from the plate, and it is usually placed about seven inches to one side of the trajectory. The rifle is located at least 10 feet farther than is

the interrupter; it may be at any greater distance as desired.

The exact position for the interrupter can be found only by trial, or by chance. Using a type of projectile the velocity of which is only approximately known, a skilled experimenter will usually find the proper location of the interrupter with from five to ten trials, by means of visual observations. With projectiles of known type, two or three shots out of five will give useful photographic records.

The photographic plates commonly used are 11 x 14 inches in size; the plate holder is placed against one wall of the cabinet. When the plate holder is removed, a white viewing-screen is uncovered. There is room in the cabinet for one, two or three observers. When all adjustments are made and the gun is fired, the observers can see the projectile in the air, and its shadow and the air waves on the screen as they would appear had a photograph been made.

In the experiments made with the apparatus described, perhaps ten thousand rounds of ammunition were fired, a considerable portion of which was in connection with the work reported to the Ordnance Department. More than a thousand photographs were made of projectiles in flight. Several photographs of general interest are reproduced in the following pages.

A solid body, such as a projectile, moving through the air leaves behind it a "wake" consisting largely of a rotational turbulence. If the speed of the projectile is greater than the normal speed of sound, the bullet produces disturbances which, at a short distance from the bullet, take the form of conical sound waves. Usually such sound waves are produced by the nose and by the base of the bullet, and by other surface irregularities. The compression originates at the nose of the bullet and is then moving with the speed of

the projectile; within a distance comparable to the length of the bullet the speed is reduced to that of sound. The generation of the wave at one speed and its propagation at a slower speed produces the conical wave; the greater the speed of the projectile, the smaller the angle of the cone.

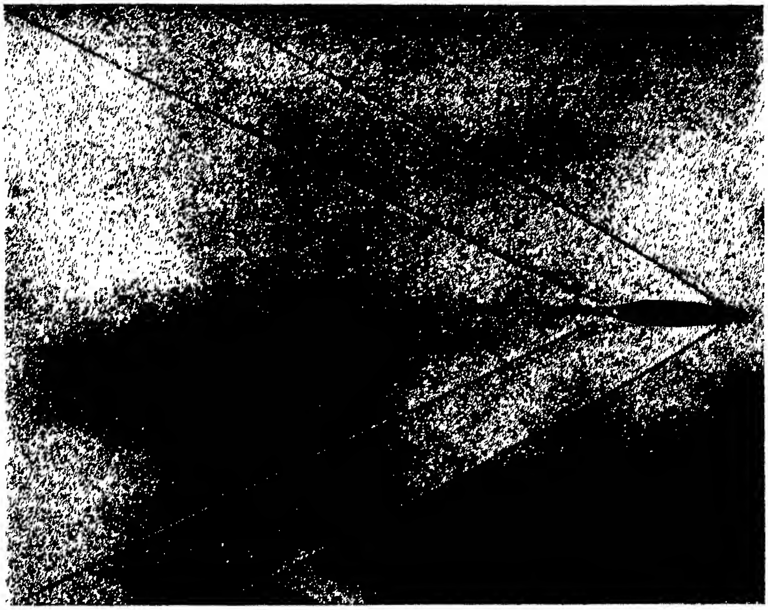


FIG. 18. Photograph of a rifle bullet moving with the velocity of 2700 feet per second, and resulting air disturbances. Time of exposure less than 1/2,000,000 second.

The variation of the angle of the conical wave with velocity is clearly illustrated in Fig. 22.

A photograph of a rifle bullet having a velocity of about 2700 feet per second, twenty feet from the muzzle of the rifle, is shown in Fig. 18. This bullet is tapered at the rear end, and is often referred to as a "boat-tail bullet." This stream-lining results in increased range. The bow wave

and the stern wave each consists of one compression and one rarefaction, very clearly marked; each is a sound wave of a single pulse. The wake behind the bullet is not a vibratory wave-motion; it is not propagated outward; it consists of a rotational turbulence which is slowly dissipated.

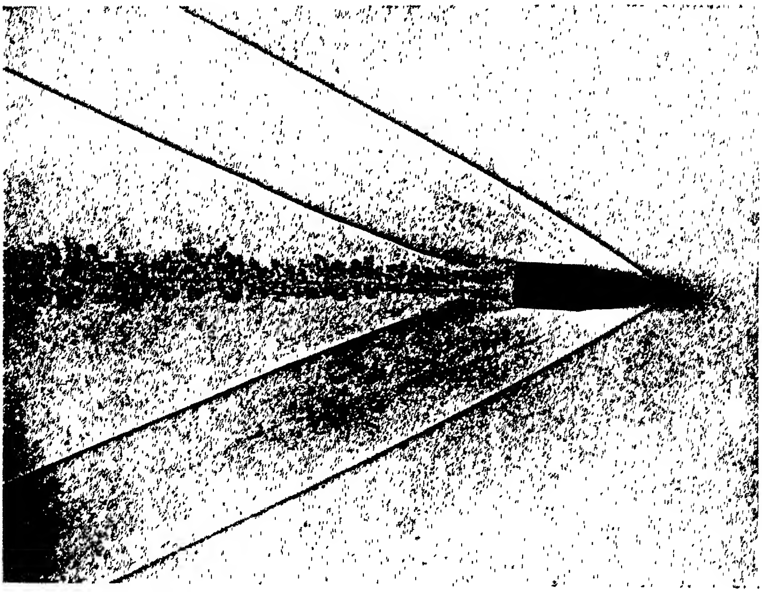


FIG. 19. Photograph of a rifle bullet in flight; velocity about 2700 feet per second. A hole has been bored through the middle of the bullet.

The photograph, Fig. 19, is that of a rifle bullet; a hole had been bored through the middle of the bullet, at right angles to its axis. It is moving with a velocity of about 2700 feet per second. The hole produces air disturbances of a rather indefinite character, which are quickly diffused. This bullet is not tapered at the rear end, and the resulting turbulence in the air has a cross-sectional area nearly double that produced by the boat-tailed bullet, causing greater re-

sistance and greatly reducing the range of the projectile.

The photograph, Fig. 20, shows the disturbances produced by a bullet, the point of which had been removed before loading. This shows the "packing" of the air in front of the bullet; the stream-lining of the nose of the bullet having been destroyed, a secondary wavelet is produced by the edge of the flat tip.

FIG. 20. Photograph of a rifle bullet in flight. The nose of the bullet had been removed by filing.

Because of improper design, or because of faulty conditions of loading or firing, a projectile in flight may be dynamically unsymmetrical with respect to its axis. This often results in "tumbling" of the bullet. Fig. 21 shows a bullet which has tumbled; this has taken place within a distance of fifty feet from the muzzle of the rifle. The air disturbances wholly lack the symmetry which is shown in

connection with a properly designed projectile. The tumbling may continue till the bullet will be moving sideways, and the trajectory becomes erratic.

A rifle bullet, the nose of which had been flattened by filing, was fired through a board of hard maple-wood with the result shown in Fig. 22. The nose of the bullet was "dum-

FIG. 21. A projectile in flight which has developed "tumbling."

dumed," or expanded by the board, and the jacket which surrounded the lead body of the bullet was torn off. The jacket is shown closely following the lead body; the other "projectiles" are fragments of the wood, moving with various velocities. The trailing particles have lesser velocities which are indicated by the less acute angles of the nose waves, as well as by their locations in the field of view.

A photograph of a soap bubble through which a rifle bul-

let has passed is shown in Fig. 23. Droplets of the soap solution have been widely scattered, but the punctured bubble has not yet collapsed.

A soap bubble which has been struck by a slowly moving

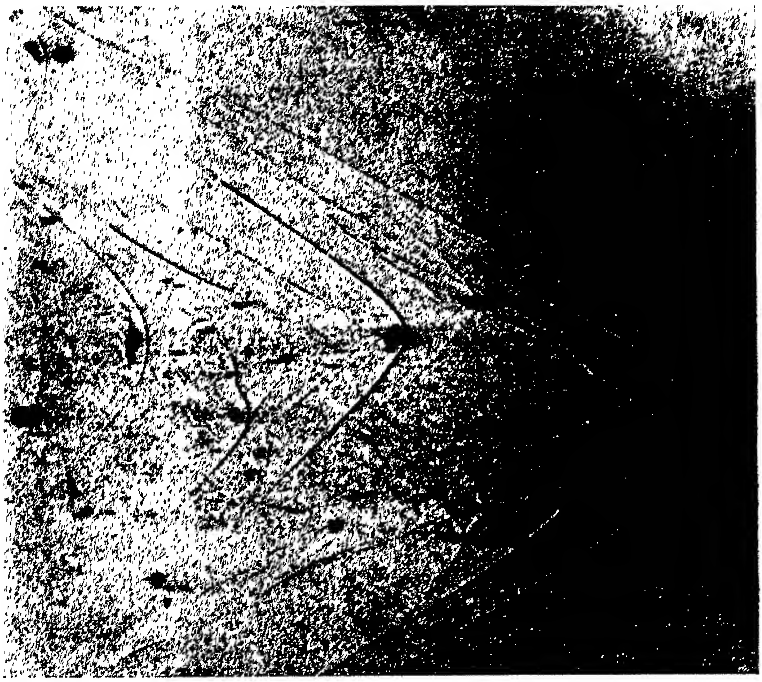


FIG. 22. Splinters of wood following a bullet with flattened nose which had been fired through a board of maple wood.

projectile, a steel ball which has fallen through a distance of eight inches, is shown in Fig. 24; the bubble is rapidly dissipated, beginning at the point of contact. If a small amount of glycerine is added to the soap solution, the surface tension is greatly increased. When a bubble of this solution is struck by the falling ball, it is not punctured,

but rather acts like a bubble of thin sheet rubber, being stretched but not broken, as is shown in Fig. 25.

The *Schlierenmethode* and the model method of Foley and Sabine are not suitable for photographing the sound waves from projectiles; however, they use the electric spark to photograph sound waves which have been produced by

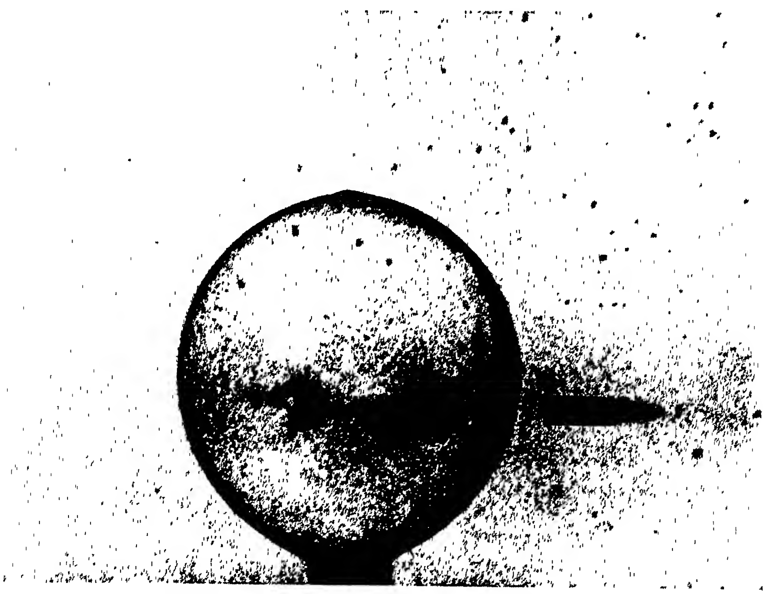


FIG. 23. A rifle bullet in flight which has passed through a soap bubble.

another spark. An illustration of each method is given for completeness.

It is inherent in the method of striae that the pictures are on a very small scale. Because of the uncertainty in the timing of the sound and recording sparks, it is necessary to take a large number of photographs, more or less at random, and to select the particular views which properly illustrate the phenomenon being studied. In Fig. 26, at the left, are

shown several "exposures" of the reflection of a sound wave by an elliptical reflector, the apparatus being arranged as described by Wood. The field lens used has a diameter of five inches; the small circles in the figure are the images of

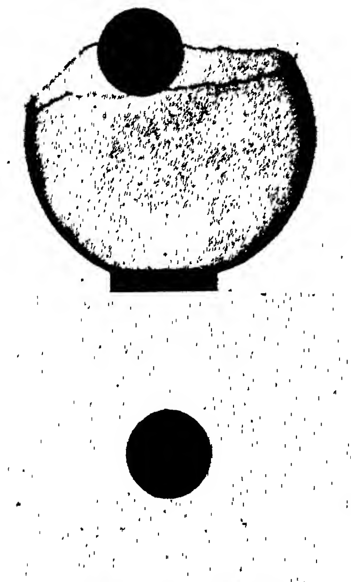


FIG. 24. A soap bubble struck by a falling steel-ball.

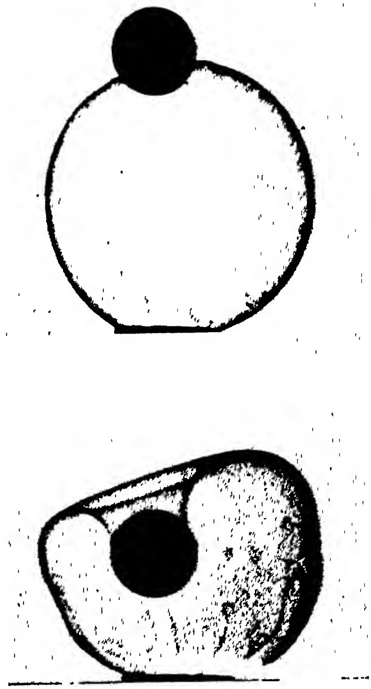


FIG. 25. A bubble of glycerinated soap solution, struck by a falling ball.

this field, here shown in the size of the original photograph. For study, such a picture must be magnified; at the right, one picture is shown magnified about eight times.

The progress of a sound wave in a model of an auditorium, photographed by the method of Foley previously described, is shown in Fig. 27. The sound originates on the

stage, located in the lower right corner of the model. The main wave is strongly marked; the confusion of waves be-

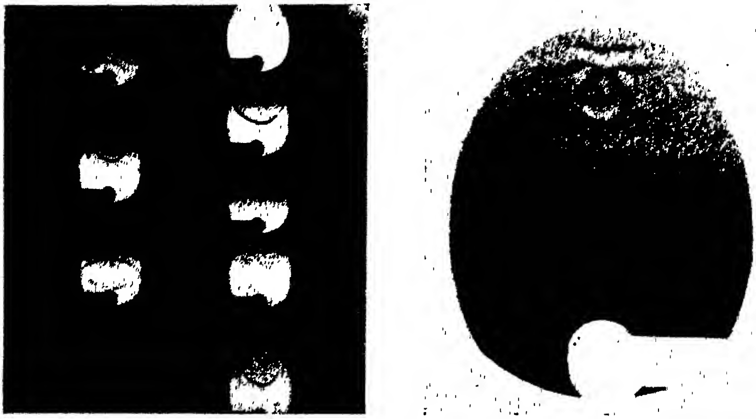


FIG. 26. Photographs of sound waves made by the "Schlierenmethode."

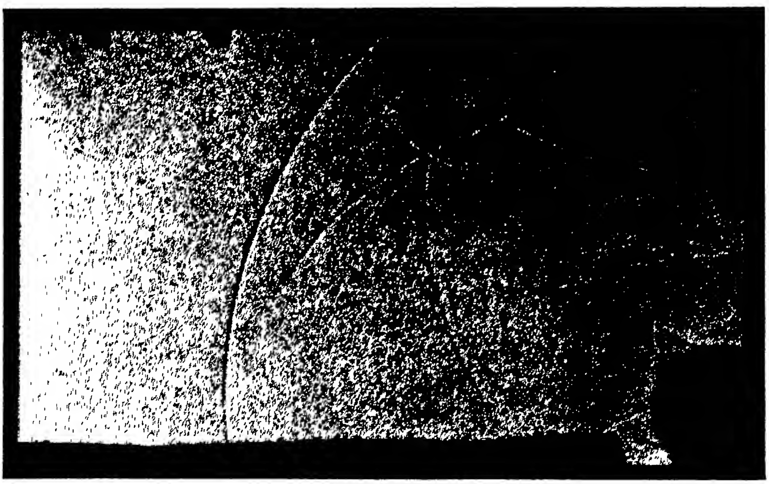


FIG. 27. Progress of a sound wave in a model of an auditorium.

hind it has developed by reflections of the one original wave impulse, and in an auditorium this confusion of sound constitutes reverberation.

For studying the development and progress of a wave motion in an enclosure, the method of the ripple-tank is often more convenient than the sound-pulse method. A sectional model of the enclosing walls is placed in a shallow tank of water; ripples are generated at a point corresponding to the source of the sound or other disturbance. The progress of the wave disturbance can be observed visually and can be photographed.[30]

PART II

THE SANDY HOOK EXPERIMENTS

PRESSURE, WAVE FORM AND VELOCITY OF SOUNDS FROM LARGE GUNS

Chapter V

RESEARCH AT SANDY HOOK PROVING GROUND

Introduction

In April, 1918, Colonel R. A. Millikan, Chief of the Department of Science and Research of the Council of National Defense (The National Research Council), requested the writer to undertake the study of the physical characteristics of the pressure waves produced in the atmosphere near large guns in action. Quantitative information in regard to these effects was desired by Dr. D. R. Hooker, of the Department of Physiology of Johns Hopkins University, who, acting under the same auspices, was engaged in an investigation of the physiological effects of air concussion, which, at the

fered with. When the Armistice was declared in November, 1918, the demands upon the facilities of the Proving Ground, which had been developed to a maximum during the War, were suddenly reduced or suspended. This gave an increased opportunity for carrying on the experiments of scientific interest. The leave of absence from teaching duties was extended and the work at Sandy Hook continued till November, 1919.

At the Proving Ground, private laboratory rooms were furnished, and the machine shops, transportation, and construction services were made available. Not only was special wiring provided when necessary, but use of the regular communication and telephone systems was permitted for signal work. The Chief Proof Officer gave advance notice of the programs of firing of large guns, and at times arranged the programs to accommodate the placing of recording apparatus and the making of observations. All conditions combined to provide extraordinary facilities for the study of sound effects of various kinds. The conditions could hardly be reproduced at any cost.

The Department of Science and Research of the Council of National Defense assigned several assistants from the enlisted personnel. Professor (now Dean) Carl F. Eyring, of Brigham Young University, assisted during the most important developmental and testing work carried on at Cleveland, and in the experiments relating to velocity and pressure at Sandy Hook Proving Ground, continuing until his discharge from the service. Following Professor Eyring, Mr. William G. Keat, Master Signal Electrician, was assigned to the experimental work at Sandy Hook. Sergeant John M. Chancellor also assisted during an important part of the experimental development. At the laboratory in

Cleveland, during the construction of new instruments. Mr. Wallace Mountcastle was regular assistant, and Mr. S. J. Papoi, the mechanician of the Department of Physics, gave valuable aid. At the Proving Ground, throughout the entire period of experimentation, other enlisted men were assigned, two being so detailed throughout the work, and any larger number was especially assigned to the work as required.

Taking advantage of this exceptional situation, the researches were extended beyond the first purpose, and led to four distinct groups of results: (1) the pressure effects in the air around large guns in action; (2) the physical characteristics of the sound waves from large guns; (3) propagation of the explosive sound from the muzzle of a large gun; (4) the normal velocity of sound in the free air. Preliminary partial reports have been made on all of these subjects in papers presented before the National Academy of Sciences, the American Physical Society, the American Philosophical Society, the Franklin Institute, and the Royal Society of Canada; but publication has been made only in the form of brief abstracts.[32] A final report covering the several phases of this work is here presented.

It was necessary to devise several new instruments and processes for these unusual studies. The firing of several thousand "rounds" from the large guns was observed during the development of the methods, and for testing and calibrating the recording instruments. Quantitative records from a total of one hundred and ninety-six firings have been used in the definitive results for the pressure and velocity of sounds. Observations for pressure were made on ninety-six firings, for the propagation of the explosive sound near the gun on sixty firings, for long-range velocity of sound

on eleven firings, and photographic records were made with the phonodeik on twenty-nine firings. Thirty-one of these rounds were fired from a 12-inch mortar, two rounds from a 5-inch rifle, seven rounds from a 6-inch rifle, nine rounds from an 8-inch rifle, eighty-eight rounds from a 10-inch rifle, forty-five rounds from a 12-inch rifle, and fourteen rounds from a 14-inch rifle.

Chapter VI

PRESSURE EFFECTS IN THE AIR NEAR LARGE GUNS IN ACTION

The Baroscope

In certain of the physiological experiments conducted at Sandy Hook Proving Ground by Dr. D. R. Hooker,[31] anesthetized animals were placed on the field, and it was essential to have measurements, made at the time of exposure, of the pressures from the gun blast at several points near the animal. It was entirely practicable to adapt the phonodeik, developed by the author and described in Part I of this work, to record the sound waves from large guns at stations where it was safe, from a physiological point of view, for a human being to work; such records are described in the following chapter of this report. The study of shell shock required that measurements be made at stations which were physiologically unsafe; it seemed sufficient to supplement the phonodeik records with determinations of the intensity of the pressure produced in the explosive sound wave. This pressure may vary from a few ounces to a thousand pounds per square inch. No instrument for this purpose was available; experiments were undertaken, at first in the laboratory, and later in the field, to develop an instrument which would be simple but certain in action, portable, and of such rugged construction as to be usable at the Proving Ground

near the large guns when being fired in the routine of the usual tests. The pressure gauge developed in 1918 for this work, which may be called a "baroscope," proved to be very practicable and efficient.[32]

The baroscope is shown in section in Fig. 28. A diaphragm of elastic material, *D*, is very tightly clamped between heavy bronze rings, *R*, so shaped that the central portion of the diaphragm is free to vibrate. These rings

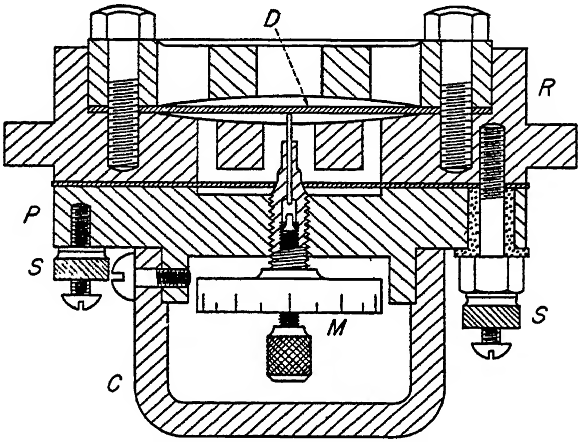


FIG. 28. Baroscope for measuring explosive pressures.

are perforated with large holes, which are open to the air on one side, and are enclosed on the other side by a heavy bronze plate, *P*; between the plate *P* and the ring *R* there is a gasket which serves the double purpose of making the joint air-tight and of insulating the plate from the ring. The screws which hold the plate and ring together are bushed with insulating material. Passing through the center of the plate is a micrometer screw, *M*; the end of the screw is split and holds by very light friction a sliding pin which is placed in contact with the center of the diaphragm.

For this pin the eye-end of a fine sewing needle has been used; the steel has an excellent polish, and the gold-plated end makes a good contact point. Two binding screws, S, are provided, one connected to the diaphragm through one of the insulated clamping screws, while the other connects directly with the plate P and the needle-pointed micrometer screw. A protecting cover C is provided for the head of the micrometer screw.

FIG. 29. Reading the baroscope.

When the diaphragm is caused to vibrate, as by the pressure wave from the explosion, the contact pin is pushed inward by an amount equal to the amplitude of the maximum displacement. The amount of this displacement is then determined by connecting the baroscope in an electric circuit with an indicating galvanometer, such as a sensitive voltmeter, Fig. 29, and turning the micrometer screw forward till contact with the diaphragm is established.

For resetting the instrument, the micrometer screw is withdrawn to its zero position and the pin is again brought

into contact with the diaphragm by means of a small push-screw working in the axis of the micrometer screw. The push-screw is finally withdrawn a turn or two to give opportunity for the pin to move inward at the next pressure measurement.

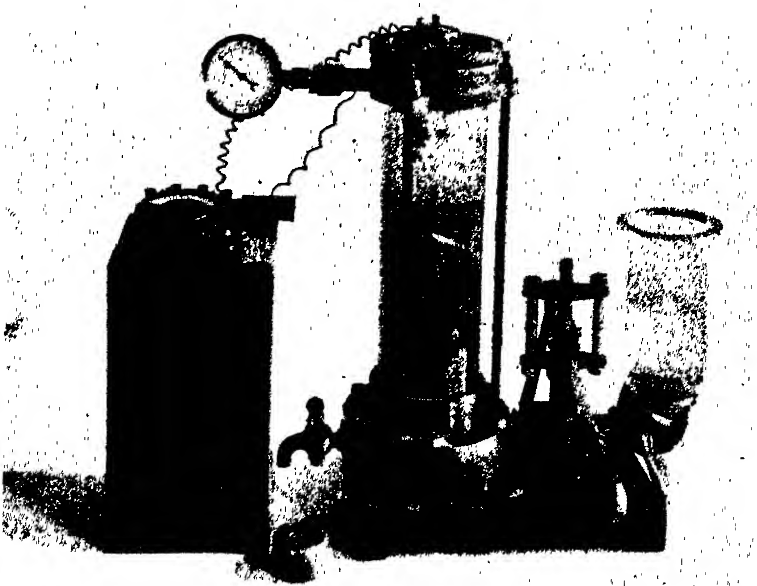


FIG. 30. Calibrating the baroscope.

The baroscope is calibrated in terms of static pressure by means of a hydraulic press provided with a standardized gauge, Fig. 30. The baroscope is clamped in a fitting on the upper end of the hydraulic cylinder, there being an air cushion between the water and the diaphragm. Each instru-

ment is then calibrated when it is in the same condition as in the field tests. It is essential that the diaphragm in this type of measuring device should have a free period which is very short in comparison with the period of the effect being studied. The lowest frequency of any diaphragm in the baroscopes and phonodeiks used in these experiments is in excess of 1100 cycles per second. The pressure being meas-

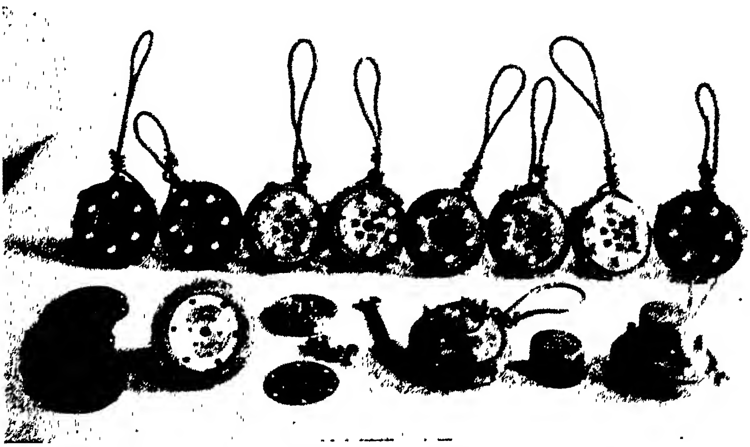


FIG. 31. A set of baroscopes.

ured is in the nature of a pulse which persists for several thousandths or several hundredths of a second; the maximum pressure of the pulse may be considered as being constant over an interval of time covering five or more periods of the diaphragm, so that the response of the latter is practically the same as if the pressure were static. This condition is well illustrated in Fig. 48.

For the rapid plotting of a field of pressure, it is desirable to have a number of baroscopes to determine the pressure at various points simultaneously. One instrument can be used

in a fixed position for successive experiments, thus tying together the various sets of readings. Two or more baroscopes may be placed in one position to give an average value as far as instrumental variations are concerned. Fig. 31 shows the group of baroscopes; the cover has been removed from one instrument and the diaphragm has been removed from another.

For pressures from a few ounces to a thousand pounds per square inch, the diaphragm may be of hard-rolled, spring brass, 75 millimeters in outside diameter, having an effective diameter inside the clamping ring of 50 millimeters. Four different thicknesses have been employed, from 0.38 millimeter to 1.66 millimeters thick. These have frequencies varying from about 1000 to 5000 cycles per second. A static pressure of 1 kilogram per square centimeter produces a displacement of the center of the thinnest diaphragm of 0.57 millimeter, and of the thickest one, 0.016 millimeter.

The baroscopes described may be used within a few feet of the muzzle of the largest gun, where a less rugged apparatus would be destroyed. For locations where it is safe for a person to remain, a baroscope on the same principle, but using a glass diaphragm, has been used. In this case the movements of the diaphragm are recorded on a moving photographic film by means of the author's phonodeik, and a complete record of the wave form, together with a time scale from a tuning-fork interrupter, is obtained. This apparatus is also calibrated in terms of static pressure by means of an air pump and a mercury gauge. With a glass diaphragm of 30 millimeters free diameter and 0.085 millimeter thick, a change of pressure of 0.16 gram per square centimeter gives a displacement of the light-spot on the photographic film of 1 centimeter; other constants are given

in Table I, in the section on "The Portable Phonodeik," Chapter II.

The usual procedure in the pressure measurements is as follows. The eleven baroscopes, each having been calibrated and set to zero, are located in the field around the gun, according to a plan. Each instrument is carefully placed on the ground, with the perforated face upwards; after the gun has been fired the instruments are removed from the field, and the pressure recorded on each is determined by the method illustrated in Fig. 29.

Observations for pressure, each consisting of the readings of eleven baroscopes, were made in connection with ninety-six firings of guns of various sizes, 6-inch, 8-inch, 10-inch, 12-inch, and 14-inch rifles, and 12-inch mortars. These observations have been analyzed to compare the pressures produced by the different types of guns, to show the distribution of pressure in different azimuths around the gun, to determine the effects of angular elevation of the gun, and to compare the pressure in the air above the ground with that observed on the ground.

The Distribution of Pressure Around Large Guns

The distribution of pressure around a 12-inch rifle is shown in Fig. 32. The gun was in a nearly horizontal position, having an "elevation" of 1° 40′; the height of the muzzle above the ground was 10 feet 8 inches. One baroscope was placed directly under the muzzle, and ten other instruments were placed on a line, *A*, in the direction of the axis of the gun, at intervals of six feet. The eleven ordinates of the curve above the axis *A*, are the pressures in kilograms per square centimeter recorded on the several

baroscopes, due to a single shot of the 12-inch rifle. The baroscopes were then placed successively on the lines *B*, *C*, *D* and *E*, having azimuths of 45°, 90°, 135°, and 180° as referred to the line of fire, *A*. The respective curves show the pressure along these lines.

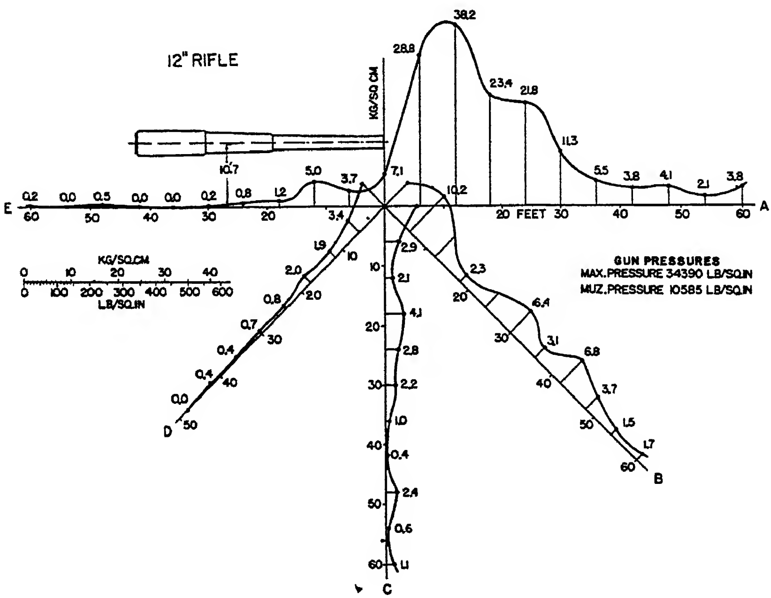


FIG. 32. Distribution of pressures around a 12-inch gun.

All of the pressures referred to in this section are the excess of pressure in the explosion wave over the normal barometric pressure at the place and time of observation.

The maximum pressure is observed on the ground twelve feet in front of the muzzle of the gun, and is equal to 38.2 kilograms per square centimeter (542 pounds per square inch). The highest pressure on any of the other lines is 10.2 kilograms per square centimeter on the line *B*, six feet from the muzzle. A pressure of 5 kilograms per square centi-

meter (71 pounds per square inch) is observed on the line *E*, directly under the gun, twelve feet back of the muzzle. At the breech of the gun, the pressure is less than 0.4 kilogram per square centimeter (5 pounds per square inch).

The distribution of pressure around a 10-inch rifle, made in the manner described for the 12-inch gun, is shown in Fig. 33. In this instance the gun is nearly horizontal, the elevation being 1° 10′, and the muzzle is 10 feet 8 inches

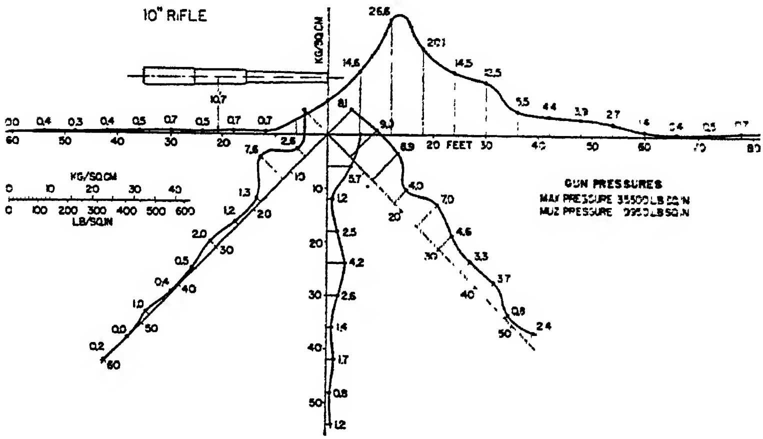


FIG. 33. Distribution of pressures around a 10-inch gun.

above the ground. The maximum observed pressure is 26.6 kilograms per square centimeter (378 pounds per square inch) on the ground, 12 feet in front of the muzzle. At the breech of the gun the pressure is less than 0.6 kilogram per square centimeter (8 pounds per square inch). The general character of the pressure is sufficiently indicated in the diagram. The pressure evidently is concentrated around a line in the axis of the gun barrel, and the pressure on the ground varies with the height of the gun above the ground. In Fig. 34 the pressures on the ground under the line of fire

are shown for a 10-inch rifle when the gun is horizontal, and when it is elevated 10°, and 14°. At an elevation of the gun of 14°, the maximum observed pressure on the ground is 8.9 kilograms per square centimeter (115 pounds per square inch).

The pressures being studied are produced by the mass of hot gas exploded from the mouth of the gun. The pressure

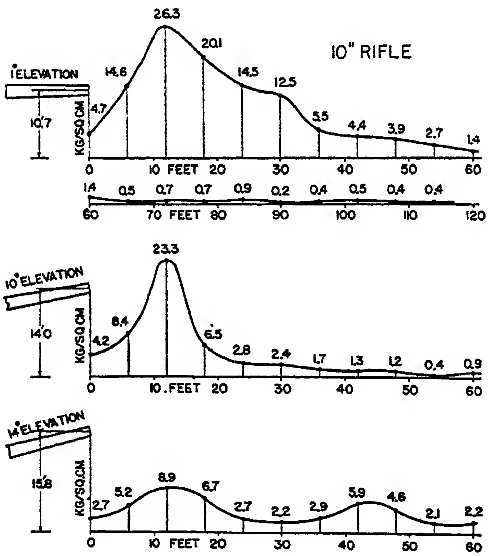


FIG. 34. Effect of elevation of gun on the pressure.

developed depends upon the quantity of powder in the charge, upon the length of time during which the burning charge is confined within the gun, and also upon the degree to which the entire powder charge is consumed in the gun. The pressures produced in the air are, then, likely to vary greatly from one charge to another; however, there is a general consistency obtained from successive charges of the same amount of powder in the same gun. Fig. 35 shows the

results of five observations of the pressures from a 10-inch rifle, two being taken on March 4, 1919, and three on the following day. The gun was elevated at an angle of 10° in all of the firings.

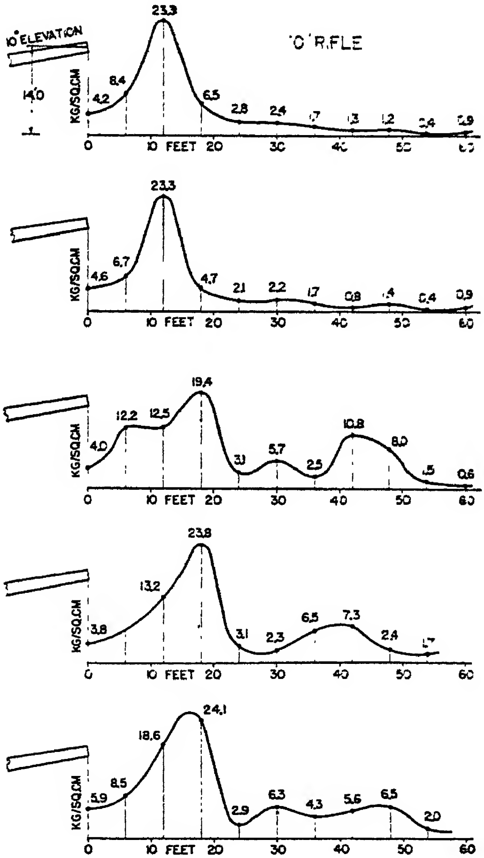


FIG. 35. Consistency of successive measures of pressure.

The pressure wave, in expanding from the muzzle of the gun, may take the form of a cone with the muzzle as apex, and the line of the projectile as axis. It might be expected

that the pressures measured in the air at equivalent points on this cone would be the same. Observations were made with a 14-inch rifle in which several baroscopes were suspended in the air; in Fig. 37, two baroscopes may be seen suspended from wires at M_1 and M_2. The results were in general accord with the expected distribution, except that the baroscope on the ground indicated a higher pressure than those in the air, in the ratio of 1.6 to 1. This increase of pressure at the surface of the ground would be expected, due to the reflection of the wave by the ground. At the particular distance from the muzzle at which the above observations were made, the ratio of the pressure on the ground to that in the free air might be expected to vary from 1.4 to 2.

Pressures for Guns of Various Types

The pressures observed from six different types of gun, a 5-inch rifle, a 6-inch rifle, an 8-inch rifle, a 10-inch rifle, a 12-inch rifle, and a 12-inch mortar, are shown in Fig. 36. The guns were all fired in a nearly horizontal line, but they were at different heights from the surface of the ground, as indicated in the figure. The maximum pressure, and also the distance to which the pressure extends, increase with the size of the gun, that is, they increase with the amount of the powder charge. The 5-inch rifle has a maximum pressure of 10.4 kilograms per square centimeter at a distance of about 5 feet in front of the gun. The 12-inch rifle produces a maximum pressure of 38.2 kilograms per square centimeter, obtained at a distance about 12 feet in front of the muzzle. The 12-inch mortar produces a maximum pressure only slightly less, 32.6 kilograms per square centimeter, but

the area of the pressure curve for the 12-inch mortar is considerably less than that for the 12-inch rifle, the propor-

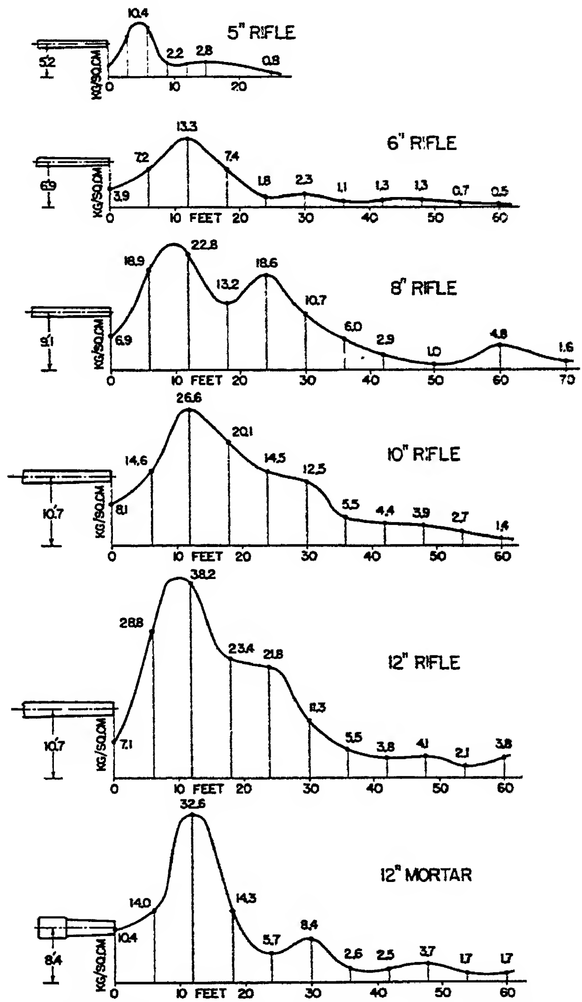


FIG. 36. Pressures from various types of guns.

tion being as 100 to 160. Both the mortar and the rifle were fired with powder charges of 700 pounds. The type of

powder, however, is quite different, due to the different lengths of the guns and, therefore, to the different times during which the pressure is being developed from the powder.

When the gun is mounted on a carriage of the disappearing type, the men operating the gun are stationed at various points on the ground and on the carriage itself located considerably in front of the breech of the gun. Observations

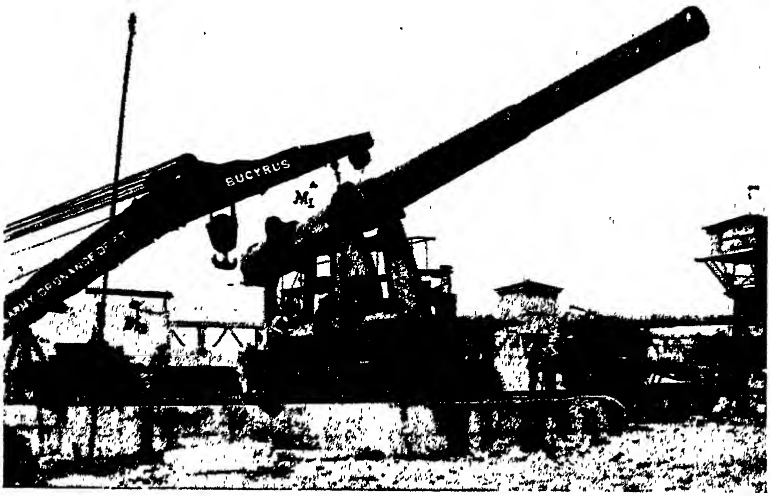


FIG. 37. A 14-inch rifle.

for pressure were made by placing baroscopes in the positions which might be so occupied. Fig. 37 is a view of a 14-inch rifle, and Fig. 38 is a plan showing the location of men operating the gun; the letters indicate the locations of the baroscopes, and Table II gives the pressures obtained at these stations. With the exception of the ranger's station, the pressures were everywhere less than 0.82 kilogram per square centimeter (12 pounds per square inch) and, as expe-

rience shows, would not be uncomfortable. The ranger is stationed in front of the carriage and is more affected by the

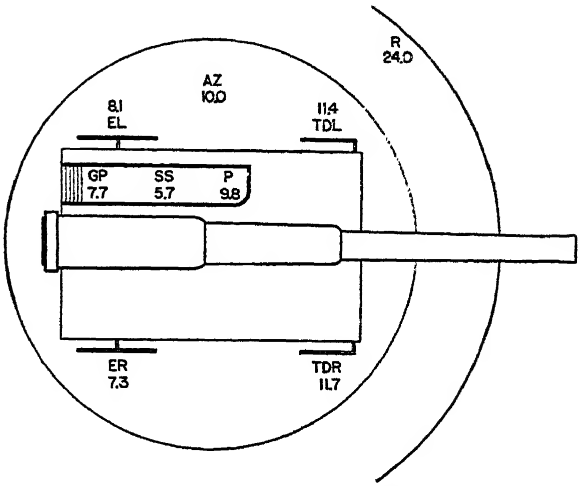


FIG. 38. Pressures around the gun. Pounds per square inch.

blast from the muzzle. Here the observed pressure is only 1.7 kilograms per square centimeter (24 pounds per square inch) and ordinarily is not dangerous.

TABLE II. Pressures on 14-Inch Gun Carriage.

Station			*Average Pressure*	
			kg/sq. cm	*lb. sq. in.*
TDR	Tripping	Right	0.82	11.7
TDL	"	Left	0.80	11.4
ER	Elevating	Right	0.52	7.3
EL	"	Left	0.57	8.1
Az	Azimuth		0.70	10.0
R	Ranger		1.70	24.2
P	Platform Front		0.67	9.8
SS	Sight Standard		0.40	5.7
GP	Sun Pointer		0.54	7.7

Physiological Effects

Regarding the physiological effects of the air concussion resulting from the discharge of large guns, Dr. D. R. Hooker makes the following comments, which have been taken from his extended report on the subject.[31]

"The data regarding the effects of gun blast on anesthetized dogs are insufficient to warrant a positive statement as to the concussion pressure requisite to produce shock. From the figures one may judge, however, that approximately 275 pounds per square inch (18 to 19 atmospheres) are necessary to establish primary shock in the case of 10-inch and 12-inch rifles. It is interesting to note that the 12-inch mortar, even when a pressure of 388 pounds per square inch was delivered, did not produce shock. Miller, in repeated observations found that this gun, which is mounted somewhat nearer the ground than the rifles, gave uniformly high pressures. The only explanation which seems to accord with Miller's observations and my own results is that the duration of the high pressure phase in the case of the mortar, is insufficient to overcome the physical resistance of the tissues. This hypothesis is supported by the fact that 288 pounds before the 10-inch rifle was less effective than 267 pounds before the 12-inch rifle, the latter presumably having the longer phase of high pressure . . . Exposure of animals, ten to twenty feet in front of 10-inch and 12-inch rifles, yielding a concussion pressure of 18 to 19 atmospheres, usually produced primary shock. This condition is essentially instantaneous in onset . . . The concussion pressure adequate to produce shock results in extensive laceration of the tympanic membrane of the ears . . . There is no evidence that the functional capacity of the heart was

affected and the valves were uninjured . . . No evidence of hemorrhage, gross or petechial, has been found in the nervous tissues . . . The blood is not hemolyzed . . . The lungs showed areas of red hepatization especially in the lower lobes, which were practically solidified . . . It is open to question whether the condition of shock in these experiments is not primarily associated with brain concussion . . . The effects are due to the duration of the phase of high pressure rather than to the height of the atmospheric pressure as such or to the tonal vibration of the atmosphere."

Marage, in France, made a study of the effects of the shocks of war,[33] and reports pressures close to a center of explosion of the order of magnitude of 150 to 300 kilograms per square centimeter. These pressures diminish rapidly and at distances of 30 meters are only 2 to 3 kilograms per square centimeter. Marage reports the following clinical facts relating to the shock effects on human beings. Some die without receiving visible wounds. Others lose consciousness, speech, memory, sight, or hearing, accompanied by intense headaches. These symptoms may continue for a few weeks or for years. The following explanation is made: The body acts like an elastic sack full of liquid which communicates directly with an undeformable sphere, the skull, filled with an isostatic liquid in which floats the brain. An increase of exterior pressure is transmitted as a hydrostatic pressure to the interior of the skull and to the brain unless the liquid finds natural obstacles to such transmission and unless the duration of the high pressure has been very brief; less than a hundredth of a second. Devices introduced into the external ear may protect the ear-drum, but they will be absolutely ineffective against shocks.

CHAPTER VII

WAVE FORM OF THE SOUNDS FROM LARGE GUNS

PHONODEIK RECORDS OF SOUNDS FROM LARGE GUNS

TWENTY-NINE photographic records of the wave form of the sounds from large guns were made at Sandy Hook Proving Ground in 1918 and 1919. These represent the sounds from a 12-inch mortar and from 6-inch, 12-inch, and 14-inch rifles, at distances varying from a hundred feet to three thousand feet, and from stations both in front of and behind the gun.

The record of the sound from a 12-inch rifle is shown in Fig. 39. The phonodeik was located at the entrance to the Headquarters and Instrument Building, about 1500 feet in the rear of the gun. The diaphragm of the vibrator was No. 1, 0.085 millimeter thick. The general shape of this pressure curve is characteristic of all the records. There is no true vibratory wave form; instead there is a positive pulse (compression), rising rather abruptly to a maximum, and falling to a negative pressure (rarefaction). The intensity of the negative pressure is usually much less than that of the compression pulse, but it continues for a longer time. On the return of the pressure to the normal value, there is some fluctuation, a billowy action having a small irregular vibratory character. The maximum pressure here recorded is 2.6 grams per square centimeter, occurring about

0.015 second after the beginning of the sound; the pressure has returned to its normal value in 0.025 second, and then becomes negative for 0.050 second or longer. The irregular billowy effects following the main pressure pulse are probably due to various reflections from near-by walls and buildings. About 400 feet in front of the guns are the sand "butts" into which projectiles may be fired. The sand is retained in position by a vertical facing of wood planks. Near the end of this record, at *e*, occurring 0.70 second after

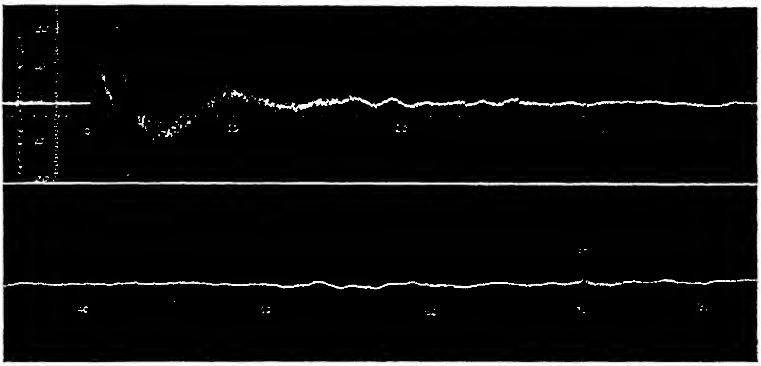


FIG. 39. Phonodeik record of the sound from a 12-inch rifle and the echo of the sound.

the first pressure, there is a miniature reproduction of the main outline of the original sound, which is clearly a reflection from the vertical face of the butts; the elapsed time is that required for the sound to travel twice the distance of the butts.

The high frequency vibrations which are prominent in this record, and which appear, more or less, in all of the records, are due to the free period vibration of the diaphragm which is excited by the sudden blow of the explosive sound. The frequency of this free period is dependent upon

the thickness and the clamping of the diaphragm, and it is also influenced by the attached mirror and by the housing, as is explained in "The Science of Musical Sounds," page 153.[16] The frequencies of the free periods are easily determined by comparison with the recorded time signals; for the record shown in Fig. 39 the frequency is 1430; for the record in Fig. 41 the frequency is 1200; for Fig. 43 it is 1440; for Fig. 48 it is 1350; and for Fig. 49 it is 1190.

A direct test of the free period of the diaphragm was made

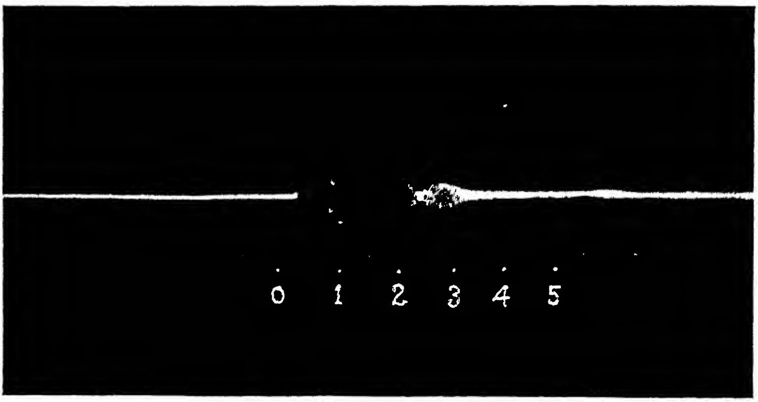


FIG. 40. Free period of the diaphragm of the phonodeik.

by photographing the spat-sound or pulse wave produced by striking two small boards together. Such a record for the diaphragm of 0.085 millimeter thickness is shown in Fig. 40. The frequency is directly computed to be 1600.

The photographic record of the sound from a 12-inch rifle is shown in Fig. 41, the phonodeik being located in observation Tower A, about 190 feet behind the gun. The observation Tower A, Figs. 37 and 63, is supported on a steel framework of only moderate rigidity, and its floor is about 60 feet above the ground. When the gun is dis-

charged, the blast from the muzzle is distinctly felt through the air, and the tower is very appreciably shaken. The effect of this vibration of the tower itself was transmitted to the entire phonodeik, and caused the blurred effect in the photographic record, Fig. 41. This vibration of the instrument is further indicated by the irregularities in the line of dots which constitutes the time signals. Diaphragm No. 3, 0.31 millimeter in thickness was used. The maximum pres-

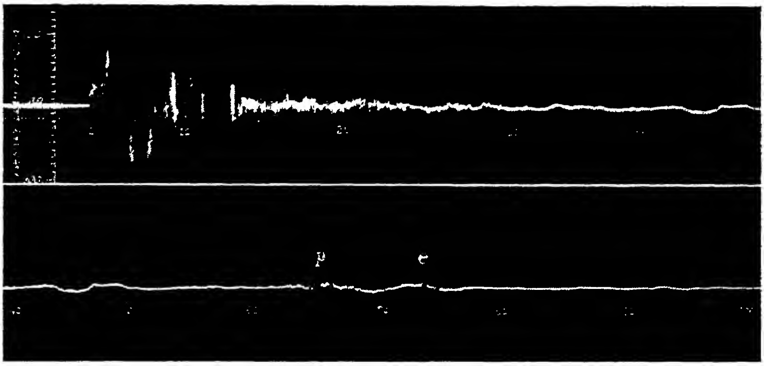


FIG. 41. Phonodeik record of the sound from a 12-inch rifle and echo of the sound.

sure of 15 grams per square centimeter is registered 0.02 second after the beginning of the sound.

In this shot the projectile was fired into a piece of thick armor plate, supported vertically against the sand butt which is located about 385 feet in front of the gun. The projectile had a velocity at the muzzle of the gun of 1268 feet per second, somewhat greater than the velocity of sound. The sound of the impact of the projectile on the armor plate is recorded by the phonodeik at *p*, Fig. 41; the sound of the boom of the gun, reflected by the face of the butt, is recorded at *e*, being the echo of the gun. Fig. 42 is

another record of the sound of the projectile striking the plate, *p*, and of the echo of the gun, *e*, showing greater detail.

The record shown in Fig. 43 is from a 12-inch rifle, the same size as used for Fig. 41; it was taken from Tower A,

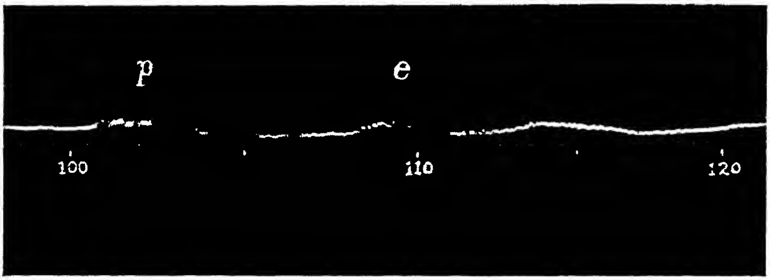


Fig. 42. Record of the sound produced by the impact of the projectile on a piece of armor plate.

but the gun was situated at a greater distance, being about 950 feet away. For Fig. 43 the phonodeik used diaphragm No. 2, 0.18 millimeter thick, and the film speed was nearly twice as great as for Fig. 41. Because of the greater distance

Fig. 43. Phonodeik record of the sound from a 12-inch rifle, distance, 950 feet.

of the gun, there is no perceptible shaking of the tower, and the details of wave form are distinct. The high frequency component, due to the free period of the diaphragm is easily measured. The maximum pressure registered in Fig. 43 is 2.1 grams per square centimeter.

With the phonodeik stationed at the Brick House, about 1330 feet from the gun, nearly at right angles to the line of fire, the record Fig. 44 was obtained from a 12-inch rifle, which produced the record shown in Fig. 43, with the same diaphragm, 0.18 millimeter thick. The maximum pressure registered here was 1.3 grams per square centimeter. The

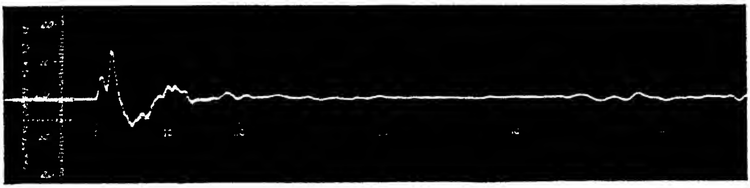


FIG. 44. Record of the sound from a 12-inch rifle, distance 1330 feet.

free period vibration of the diaphragm is much reduced, and appears in the record like beads on a string.

A 6-inch rifle about 1200 feet from the Brick House location gave the record shown in Fig. 45, which was made with the sensitive diaphragm No. 1, 0.085 millimeter thick. The

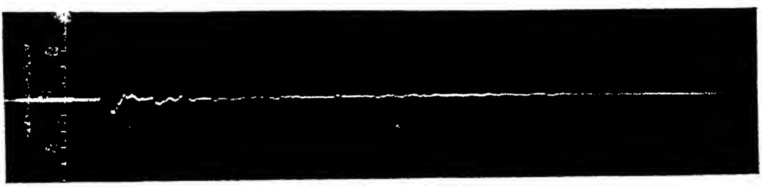


FIG. 45. Record of sound from a 6-inch rifle.

maximum pressure recorded is 0.2 gram per square centimeter. This shock hardly excites the free period of the diaphragm, but the general characteristics of the record are the same as for the more intense explosion.

When these studies were proposed there was a lively interest in the possible solution of the seeming paradox that when a large gun is fired, the glass windows of near-by build-

ings are often broken, and the fragments of glass always fall outwards instead of inwards; the latter effect would seem to be the more probable as the result of an explosion. The first photograph of the wave indicated the answer to this question, and all the photographs show the same general characteristics. The first positive pressure may be sufficient to crack the glass of a window, but its duration usually is less than a fiftieth of a second; there follows a prolonged negative pressure which acts on the broken glass to pull it outward before there is time for it to fall inward.

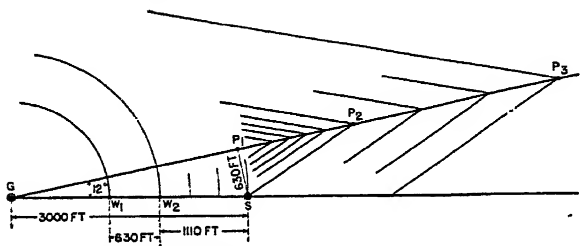


FIG. 46. The propagation of the shell and gun waves from a large cannon.

SOUNDS FROM LARGE PROJECTILES IN FLIGHT

When the observing station is located in front of the gun, sound effects called the "crack" are received from the projectile itself, in addition to the sound from the muzzle of the gun called the "boom." In Fig. 46, the relations of the two effects are illustrated. The gun, G, is assumed to have an elevation of 12°, and the projectile moves along the path $G\,P_3$ with a velocity of 2600 feet per second, while the boom sound travels with a velocity of about 1120 feet per second. The observing station, S, is 3000 feet in front of the gun. The nearest approach of the projectile is at P_1 at which time the boom has progressed only to W_1. The crack sound of the passing projectile at P_1 then travels as a sound wave to S, a distance of 630 feet; when the crack arrives at

S and is heard, the projectile has progressed to P_2, while the boom has also traveled 630 feet and is at W_2, still 1110 feet distant from the station. About one second after the crack has been heard, the boom wave arrives and is heard in turn; at this time the projectile is at P_3. A 14-inch projectile is shown in Fig. 47; its weight is 1400 pounds and a charge of 700 pounds of powder gives it a muzzle velocity

FIG. 47. A 14-inch projectile.

of 2600 feet per second. Fig. 48 is the phonodeik record of the crack from such a 14-inch projectile and of the boom from the rifle from which it was fired, recorded under the conditions just described. The crack shown in the upper line consists of two sharp compression pulses about 0.02 second apart, with a negative pulse between them, and followed by irregular shallow waves. The main pulses are due to the bow and stern waves of the projectile, while the ir-

regular waves are produced by the turbulence left by the projectile as it plows its way through the air. The general character of these waves is referred to in a later section, and is illustrated in Fig. 60. The boom sound consists of a short

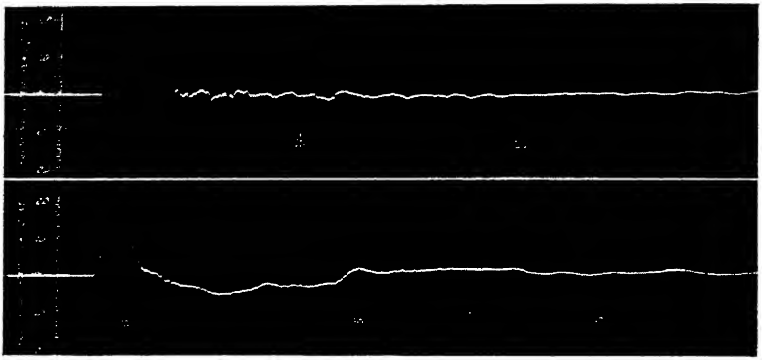


FIG. 48. Phonodeik record of the shell and gun waves from a 14-inch rifle.

positive pulse, corresponding to a compression of about 2.2 grams per square centimeter, lasting for 0.015 second, followed by a rarefaction of less than 0.5 gram per square centimeter, lasting for about 0.10 second.

FIG. 49. Phonodeik record of the shell and gun waves from a 12-inch rifle.

Fig. 49 is the record of the crack of the projectile and the boom of a 12-inch rifle, recorded at a station located about 600 feet in front of and about 300 feet to the side of the gun. The maximum pressure here recorded is about 1.4 grams per square centimeter; the general character of the phenomena is as described for Fig. 48.

Chapter VIII

THE PROPAGATION OF THE SOUND WAVE FROM THE MUZZLE OF A LARGE GUN

The String Galvanometer and Microphones

Extended preliminary studies beginning May 9, 1918, were made for the development of methods and instruments for recording the velocity of propagation of the sound waves in all directions around a large gun in action. The experimental investigations were made at various places, Sandy Hook Proving Ground, Erie, Baltimore, Princeton Sound Ranging Station, New York City, Washington, and in the laboratories of Case School of Applied Science. These studies led to the adoption of the string galvanometer and microphones for the velocity measures.

The type of galvanometer selected was that developed by the Corps of Engineers of the War Department in coöperation with the Western Electric Company for the sound-ranging service in France.[34] The principle is that of the Einthoven string galvanometer, as modified by Dr. H. B. Williams. There are six strings for making simultaneous records from six independent stations. In the Army service, the motions of the strings are recorded on a strip of photographic paper 1⅜ inches wide, moving at the rate of two inches per second. For such records a small incandescent lamp is a sufficient source of illumination. A more detailed

record was required for the investigations here to be made. A photographic film of the highest sensitivity, in a special film box arranged for a variable speed of film, was adopted; the film is 2¾ inches wide and is usually moved at the rate of five feet per second. The source is a fifteen-ampere electric arc-lamp. The galvanometer, arc light and special film box, together with six microphones and the necessary batteries and resistances for tuning, are shown in Fig. 50.

The string galvanometer is used to determine the time interval between two events, in these experiments not exceeding twenty seconds; a precision of at least a thousandth of a second is required. Fig. 52 is a portion of a galvanometer record; at the left the six horizontal lines represent the records of the six strings. There are six independent listening stations at each of which is a microphone; each microphone is in a separate and complete electric circuit with its corresponding string. As long as there is quiet at a station, the corresponding string is still and its record is a straight line. When a sound is "heard" by the microphone there is a disturbance of its electric circuit which causes the string to vibrate in the galvanometer field, and the record shows this movement. For the velocity determinations, the time of the beginning of the string movement is to be determined.

Near the slit which defines the light path there is a small synchronous motor, the armature of which carries a very light wheel with ten slender spokes so arranged that as the wheel rotates, each spoke in turn passes in front of the slit, interrupting the light and registering the equally spaced vertical lines on the moving film, as shown in Figs. 51 and 52. The motor is controlled by a standardized tuning fork which has an electro magnetic drive. The nominal fre-

quency of the fork is 50 vibrations per second, and the motor is so adapted that the time signals on the record are one-hundredth of a second apart. The "zero" spoke of the time wheel is of double width and the fifth spoke is of double width for half its length, to facilitate the counting of the time intervals; from one heavy mark to the next is ten intervals and is equal to a tenth of a second.

The fork used in these experiments was calibrated by photographically recording the sound from a Koenig standard fork which had itself been calibrated with great precision by means of a Koenig clock-fork used in connection with the standard clock of the Physical Laboratory of Case School of Applied Science. The method is described in "The Science of Musical Sounds," page 40, and the standard fork is shown on page 51.[14] The time interval for the galvanometer and fork used in the velocity determinations made at Sandy Hook Proving Ground was found to be 0.01000551 second.

The Western Electric Company, of New York, designed and constructed twelve microphones especially adapted to the study of the sounds from large guns. Six of these microphones are for high-pressure work, suitable for recording the sounds from the largest gun at stations within a few feet of the muzzle. A second set of six microphones is of great sensitivity for use at distances up to several miles from the gun. All the microphones were made as nearly aperiodic as possible, and were designed and mounted so as to be free from disturbances which might come through the supports. Commonly the microphones were hung on wooden posts by means of heavy rubber bands, at a height of about four and a half feet above the ground. Each microphone is connected by means of a complete independent circuit to one string

of the recording galvanometer, six microphones being used at one time, distributed over the field in any desired manner. The circuits are "tuned" by the separate adjustment of the voltage, resistance and capacity of each circuit. The recording apparatus was installed in the instrument room at the Headquarters of the Proving Ground, and the microphones

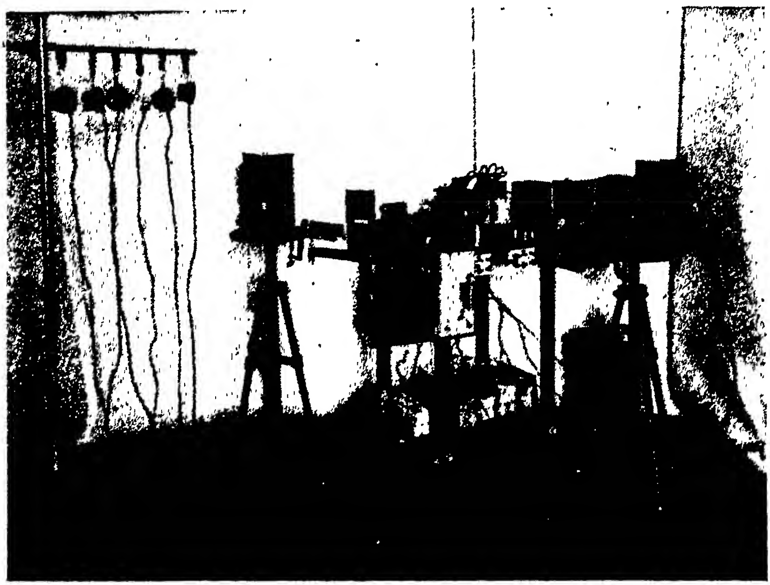


FIG. 50. A string galvanometer with six microphones.

were connected through the regular service cables or by special wires when necessary.

For testing the certainty of action, the six microphone circuits were set up and adjusted, and the microphones were placed near and all at the same distance from a small cannon; the cannon was discharged and produced the record shown in Fig. 51. The microphones were then distributed at measured distances from the cannon and gave the record

shown in Fig. 52 in which the recorded time intervals were found to be appropriate to the respective distances to the nearest thousandth of a second. These tests show that the microphones and galvanometer operate consistently.

As a further indication of the suitability of these instruments for field work, it may be stated that one microphone was attached to the muzzle of a 10-inch rifle by means of

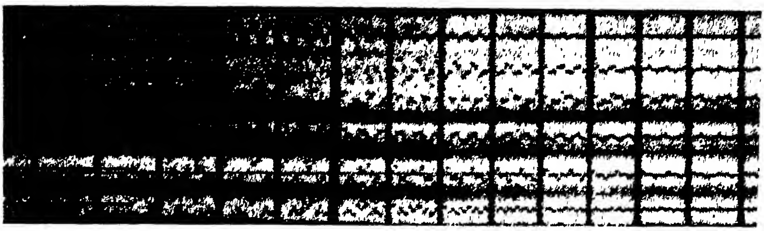


FIG. 51. Test of microphones and galvanometer.

FIG. 52. Galvanometer record of the arrival of sound at six different stations.

heavy rubber bands, where it remained during the firing of fifty-one rounds; another microphone was located one hundred feet in front of the 10-inch gun, directly under the line of fire, where it remained for two months during which time more than two thousand rounds were fired. Both microphones functioned perfectly and were in good working order at the end of the tests.

Theoretical Formula for the Propagation of Explosive Sounds

The usual differential equation for the propagation of sound in air, according to which a plane wave is propagated without change of form, is obtained by neglecting certain terms, this procedure being based upon the assumption that the amplitude is very small in comparison with the wave length of the sound. In the case of sounds from loud explosions, this assumption is not justified and the amplitude must be considered as of appreciable magnitude and effect. Much theoretical work has been done in connection with the propagation of sounds of finite amplitude, by Poisson, Stokes, Ernshaw, Riemann, Rayleigh and others, leading to the conclusion that the velocity will be much increased, the velocity at any point depending upon the condensation.[35] The most complete discussion is that of Riemann who shows that the velocity of the explosive sound at a distance x from the source is

$$V_E = V\sqrt{1 + \frac{k}{x^2}},$$

V being the normal velocity of sound for the given meteorological conditions and k a factor depending upon the condensation.

Numerous measurements of the increase in the velocity of sound waves of finite condensation have been made.[36] When the source of the explosive sound is a stationary charge of powder or dynamite, so that the condensation is transmitted equally in all directions, the experiments give results which are fairly consistent with the Riemann equation. However, when the source is the discharge of a large

gun, which is directed nearly horizontally, the conditions o. condensation assumed by Riemann are not fulfilled, and the equation fails to give the observed velocities which vary greatly in different azimuths.

Before presuming formulae, and before developing a theory for the propagation of sound in the vicinity of a large gun, it seemed best to determine the form of the wave front by direct observations made on the line of fire, at right angles to this, and on a line making an angle of 45° with the axis. Six microphones were used at one time, being variously distributed for the several observations. In one arrangement, one microphone was in the electric gun-firing circuit, another was suspended by heavy rubber bands directly from the muzzle of the gun, and the others were at distances of about 50 feet, 100 feet, 200 feet and 400 feet from the muzzle of the gun. At other times, other stations at distances of about 600 feet, 1000 feet, and 2000 feet were used; often all six microphones were placed in the field.

Seventy-one sets of measures were made relating to the velocity of the propagation of the sound wave, the source of the sound being a 12-inch mortar, a 6-inch rifle, an 8-inch rifle, a 10-inch rifle, a 12-inch rifle, or a 14-inch rifle. The distances between the principal stations had been determined with high precision for the regular purposes of the Proving Ground, and many supplementary surveys were made for these experiments. In addition to the meteorological observations of the United States Weather Bureau at Sandy Hook and of those of the Proving Ground, several sets of special observations were made for this work. At the time of observation, for every velocity determination, there were at least four sets of meteorological observations taken at different points over the field, consisting of records of the

temperature, wind velocity, barometric pressure and humidity.

In accordance with the information then available, it was presumed that the velocity of the sound from the gun over considerable distances would be much greater than the normal velocity of sound. The greatest velocity naturally was expected along the line of fire (the axis); it was thought that the velocity along any inclined line would be less than along the axis, but because of the intensity of the sound that even at right angles to the axis, the velocity would still be greater than normal. Simple approximate calculations led to the surprising and disturbing result that on a line at right angles to the axis, the apparent velocity was sometimes less than normal.

For a preliminary study, certain of the observations, after being corrected for temperature, wind velocity, humidity and rate of the tuning fork, were plotted as to time and location of station to show the actual form and position of the wave front at intervals of 0.1, 0.2, 0.3 and 0.4 second after the origin of the sound, Fig. 53. The microphones were located on the line of fire, and on lines making angles of 42½° and 81° with the axis.

The cross marks show the locations of the wave front determined directly from the observations. It was presumed that the trace of the wave front on a plane containing the line of fire would be symmetrical about this line as an axis. Instead of the expected quasi-elliptical wave front, the preliminary graphical analysis showed that the observed points lie on circles, the centers of which are at the points 1, 2, 3 and 4 on the axis in front of the gun. The expanding wave front is always a circle, the virtual center of which moves forward from the muzzle of the gun along the axis with a

velocity, the initial value of which depends upon the kind and size of gun and the charge of powder. The velocity of displacement of the center diminishes rapidly, probably being an exponential function of the time. The radius of the circle at any given time after the origin of the wave is the distance sound would travel in air in this time with the

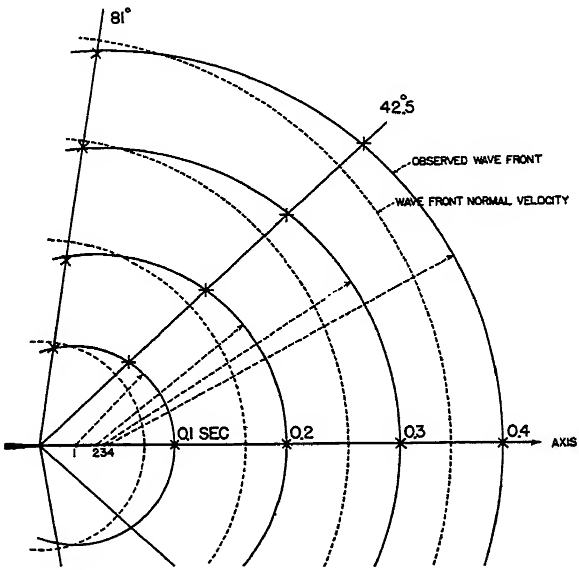


FIG. 53. Wave fronts charted from actual observations.

uniform normal velocity of sound for the given meteorological conditions. In Fig. 53 the dotted lines show the distances to which sound would have traveled with normal velocity, measured from the muzzle of the gun. The actual wave fronts are simply these circles displaced along the axis. The seeming anomaly of a sub-normal velocity in a lateral direction was due, as is evident from this figure and also from Fig. 59, to the measurement of the distance of the

wave front from the muzzle of the gun instead of from the true center of the wave front.

The physical significance of this view is that the virtual source of the sound and the center of the developing wave front in its beginnings, are in effect shot out of the gun, with a speed which may be in excess of that of the projectile itself. The speed of this expanding sphere of condensed gas is rapidly damped by the atmosphere, and its advance is reduced exponentially to a zero value. The wave front develops in such a manner that if the distance which the sound is considered to have traveled is measured from the moving virtual instantaneous center, instead of from the muzzle of the gun, the velocity of the wave front is constant in all directions, and is always the normal velocity of sound for the given meteorological conditions. In accordance with the preceding explanation of the explosive effect of the discharge of the gun, the equation of the wave front when the muzzle of the gun is taken as the origin, is that of a circle with a moving center, as follows:

$$[x - a\,(1 - e^{-bt})]^2 + y^2 = V^2 t^2,$$

a being the maximum displacement of the center along the axis, b the damping coefficient of the air for this displacement, t the time elapsed since the origin of the sound at the muzzle of the gun, and V the normal velocity of sound in air under the given meteorological conditions.[32] This is equivalent to the assumption that the explosive force acting on the sphere of expanding gas discharged from the gun is proportional to the distance of the instantaneous center from its final position when the steady state has been attained. This distance is

$$s = a\,e^{-bt},$$

and the acceleration is

$$\frac{d^2 s}{d t^2} = a\, b^2\, e^{-bt} = b^2\, s.$$

If M is the mass of the gas in motion, the instantaneous force acting on it is

$$F = M\, b^2\, s.$$

This force is related to the internal pressure, muzzle velocity, temperature of the ejected gases and other thermodynamic conditions of the gun discharge.

For the complete definition of the wave front it is only necessary to determine experimentally the propagation along the axis for the given gun and charge of powder. The position of the wave front on the line of fire at a given time t is,

$$x_t = V\, t + a\, (1 - e^{-bt})$$

and the velocity is,

$$V_t = \frac{d\, x_t}{d\, t} = V + a\, b\, e^{-bt}$$

while the initial velocity, when $t = 0$, is

$$V_{t=0} = V + a\, b.$$

The observations consist of records of the time intervals between the arrivals of the sound at a series of six stations, whose distances from the muzzle of the gun are known, and of a very complete set of meteorological data from several stations. The exact time of the origin of the sound at the muzzle is, in general, unknown, so that the first time in-

terval is one of the unknown quantities. The equations of observation then have the forms:

$$
\begin{aligned}
x_1 &= V\, t_1 &&+ a\,(1 - e^{-bt_1}) \\
x_2 &= V\,(t_1 + t_2) &&+ a\,[1 - e^{-b(t_1 + t_2)}] \\
x_3 &= V\,(t_1 + t_3) &&+ a\,[1 - e^{-b(t_1 + t_3)}] \\
x_4 &= V\,(t_1 + t_4) &&+ a\,[1 - e^{-b(t_1 + t_4)}] \\
x_5 &= V\,(t_1 + t_5) &&+ a\,[1 - e^{-b(t_1 + t_5)}] \\
x_6 &= V\,(t_1 + t_6) &&+ a\,[1 - e^{-b(t_1 + t_6)}]
\end{aligned}
$$

in which $x_1, x_2, \ldots x_6$, are the measured distances from the muzzle of the gun, and $t_2, t_3, \ldots t_6$, are the time intervals from station 1 to each of the following stations; the unknown quantities are:

$V =$ the velocity in given meteorological conditions
$t_1 =$ interval of time between origin of sound and its arrival at first station
$a =$ the maximum displacement of the center of the wave
$b =$ the damping coefficient of the air.

By subtraction, the number of equations is reduced by one:

$$
\begin{aligned}
x_2 - x_1 &= V\, t_2 + a\, e^{-bt_1}\,(1 - e^{-bt_2}) \\
x_3 - x_1 &= V\, t_3 + a\, e^{-bt_1}\,(1 - e^{-bt_3}) \\
x_4 - x_1 &= V\, t_4 + a\, e^{-bt_1}\,(1 - e^{-bt_4}) \\
x_5 - x_1 &= V\, t_5 + a\, e^{-bt_1}\,(1 - e^{-bt_5}) \\
x_6 - x_1 &= V\, t_6 + a\, e^{-bt_1}\,(1 - e^{-bt_6})\,.
\end{aligned}
$$

In general there are more equations than there are unknown quantities, and a least-squares solution, suggested by Dean T. M. Focke of Case School of Applied Science, has been adopted.

The unknown quantities are V, t_1, a, and b. Since b and t_1 are involved exponentially, a direct solution is impossible.

Let V and ae^{-bt_1} be the variables, then the normal equations with respect to these variables are:

$$V\,\Sigma\, t^2 + a\, e^{-bt_1}\,\Sigma\, t(1-e^{-bt}) - \Sigma\,(x-x_1)t = 0$$
$$V\,\Sigma\, t\,(1-e^{-bt}) + a\, e^{-bt_1}\,\Sigma(1-e^{-bt})^2 - \Sigma\,(x-x_1)\,(1-e^{-bt}) = 0.$$

A value for b is assumed and the summations are computed. Two linear equations in V and $Z = ae^{-bt_1}$ will be obtained.

$$A_1\,V + B_1\,Z - C_1 = 0$$
$$A_2\,V + B_2\,Z - C_2 = 0.$$

The solution of these equations is as follows:

$$V = \frac{\begin{vmatrix} C_1 & B_1 \\ C_2 & B_2 \end{vmatrix}}{\begin{vmatrix} A_1 & B_1 \\ A_2 & B_2 \end{vmatrix}} \quad \text{and} \quad Z = \frac{\begin{vmatrix} A_1 & C_1 \\ A_2 & C_2 \end{vmatrix}}{\begin{vmatrix} A_1 & B_1 \\ A_2 & B_2 \end{vmatrix}}$$

yielding approximate values of V and ae^{-bt_1}.

These values of V and ae^{-bt_1} when substituted in the equations derived from the observations, give a set of five residuals. Another value of b is then assumed and the entire calculation is repeated. This is continued till values for the unknown quantities are obtained for which the sum of the squares of the residuals is a minimum, constituting the least-squares solution.

In this manner the values of V, b, and Z are obtained; but Z is a function of a and t_1, the remaining unknowns, and is also exponential in form. To obtain the values of a and t_1, the now known values of b and V are substituted in the equations which have been obtained from the equations of observation by subtraction, and the logarithms of both sides of the five equations are taken. The unknowns are now $\log a$ and t_1. From this new set of equations, normal equations are formed and a and t_1 are determined, by the method of least squares.

The constants a, b, and t_1 are best obtained from observations in which the microphones are placed near the muzzle of the gun, while observations in which the microphones are distributed over a long range will yield the most precise value of the velocity, V.

When observations are made in the open air, corrections must be applied for the effects of the temperature of the air, θ; for the barometric pressure B in centimeters of mercury, and for the humidity which is represented by the vapor tension, S, in order to obtain the value for the velocity of sound under standard conditions. If V is the velocity observed under given conditions, and V_0 is the velocity in dry air at 0°C, and barometric pressure of 76 centimeters, then

$$V = V_0\sqrt{\frac{1 + a\,\theta}{1 - \frac{S}{B}\left(\frac{\gamma_w}{\gamma_a} - \frac{M_w}{M_a}\right)}},$$

γ_a and γ_w being the ratios of the specific heats for air and water vapor respectively, and M_a and M_w being the molecular weights of air and water vapor, and α the coefficient of expansion of a gas at constant pressure. The derivation of these corrections is explained in the references.[37]

The formula for the wave-front of the explosive sound from a large gun under given meteorological conditions, at a time t after the discharge of the gun, the muzzle of the gun being taken as the origin of coördinates, based upon the normal velocity of sound V_0, is then (neglecting small quantities of higher orders)

$$[x - a\,(1 - e^{-bt})]^2 + y^2 = V_0^2 t^2 \left[1 + a\,\theta + \frac{S}{B}\left(\frac{\gamma_w}{\gamma_a} - \frac{M_w}{M_a}\right)\right].$$

The quantity $a(1 - e^{-bt})$ is the displacement along the axis of the virtual source of sound due to the explosive effect,

while the second member of the equation is the radius of the circular wave front.

If there is a wind, the medium as a whole is uniformly displaced and the wave front remains a circle of the same size as in a still medium, but is displaced in the direction of the wind by the full amount due to the velocity of the wind. Where the air currents are excessive, irregular and distorted, it is impracticable to make adequate corrections for the wind. Under the conditions of scientific observation with steady and moderate winds, the simple geometric correction is ample.

Observed and Calculated Velocities

The seventy-one sets of microphone observations have been reduced in fourteen sets by the method here described. Certain constants and results are given in Table III, showing how these quantities vary with the type of gun and with the internal pressure of the gun and the muzzle velocity of the projectile. Having obtained the constants for a given gun and conditions of firing, the curves of velocity may be calculated.

Table III. Constants of Velocity Equation.

Curve	*Maximum Internal Pressure*	*Muzzle Velocity of Proj.*	*Calculated Velocity of Pulse* $V_{t=0}$	*Constants* a	b
A	33,210 lbs/sq in	2400 ft/sec	2461 ft/sec	85.87	16
B	33,600	2343	2347	69.98	18
C	16,250	1746	1735	31.63	20
D	35,500	1814	1713	89.41	7
E	21,500	1235	1242	31.05	5
F	16,900	1071	1147	89.85	1

The curves thus calculated for a 10-inch rifle corresponding to the conditions *A*, *B*, and *C*, of Table III, are shown in Fig. 54; Fig. 55 shows the velocity curves for a 12-inch

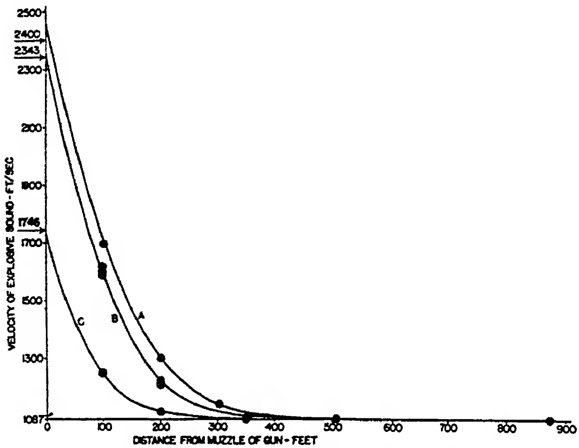


FIG. 54. Calculated and observed velocities of sounds from a 10-inch rifle.

mortar for the conditions *D*, *E*, and *F* of the table. The dots in circles indicate the actual microphone observations; the calculated curves fit these observations almost exactly.

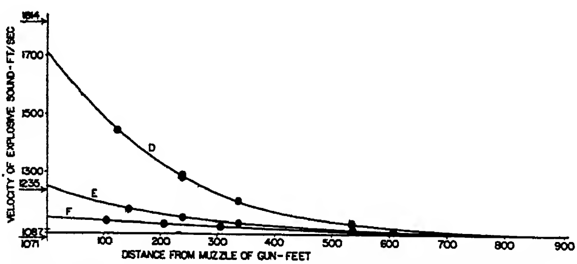


FIG. 55. Calculated and observed velocities of sounds from a 12-inch mortar.

The calculated velocity of the sound pulse for the time $t = 0$ agrees very well with the observed muzzle velocity of the projectile, taken from the records of the Proving

Ground. In four of the six trials here reported, the initial velocity of the sound is greater than the muzzle velocity of the projectile; undoubtedly the explosive gas is ejected from the gun with this excessive speed. In the case F, the projectile has a velocity less than that of sound, while the calculated velocity of the pulse is only about 60 feet per second above the velocity of sound; under these conditions the damping factor, $b = 1$, is very small, and the center of disturbance is pushed forward by the largest amount noted, nearly 90 feet. The excessive velocity is due not only to the mechanical movement of the gas, but is also greatly influenced by its internal thermodynamic condition; the temperature of the ejected gases undoubtedly varies greatly with different tests, and often particles of the powder not yet ignited are ejected with the gases and may add to the external pressure effects. This latter condition might well occur with the short-barreled mortar-type of gun.

The greatest initial velocity of the sound which has been observed is just above that of the projectile and is about 2500 feet per second. Calculation shows that the wave front of the sound from the 10-inch rifle, condition B of Table III, has advanced in 0.5 second to a distance of 650 feet from the muzzle of the gun, and that at this distance its instantaneous velocity is only 0.10 foot per second in excess of the normal velocity of sound. At a distance of 725 feet its excess of velocity is 0.05 foot per second, at 825 feet distance the velocity is only 0.01 foot per second above normal; while at a distance of 950 feet from the gun, attained in 0.8 second, the velocity of the wave front does not exceed the normal velocity of sound by as much as a thousandth of a foot per second. These conditions are shown graphically in Figs. 54 and 55.

The exponential equation here developed agrees with the experimental determinations almost exactly, while the Riemann quadratic equation fails to account for the observed velocities. The dots in circles in Fig. 56 represent the observations for the sound from a 10-inch rifle, condition *B* of Table III; the full-line curve is the velocity curve calculated by the exponential formula of this paper; the dotted

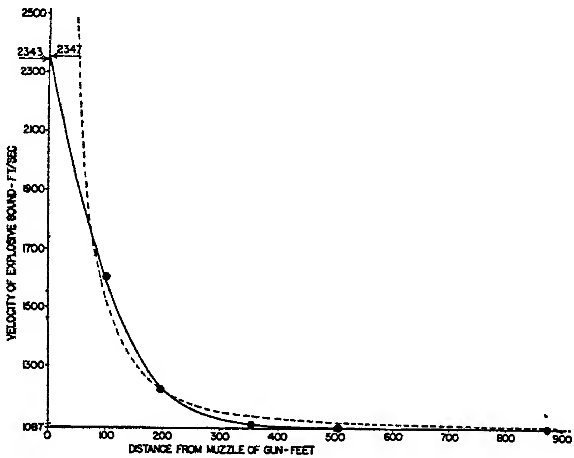


FIG. 56. Velocities of explosive sounds calculated by the exponential formula and by Riemann's formula, compared with observed values.

line is the velocity curve according to Riemann's formula. The exponential formula gives an initial velocity for the time $t = 0$, which is very nearly the velocity of the projectile as it leaves the muzzle of the gun; the Riemann formula gives an infinite velocity for $t = 0$. The velocities of the Riemann formula approach the normal velocity much too slowly to fit the observed velocities. It seems probable that an exponential formula with appropriate constants will best represent the velocity of an explosive sound of any kind; such a formula starts with a finite excess of velocity and

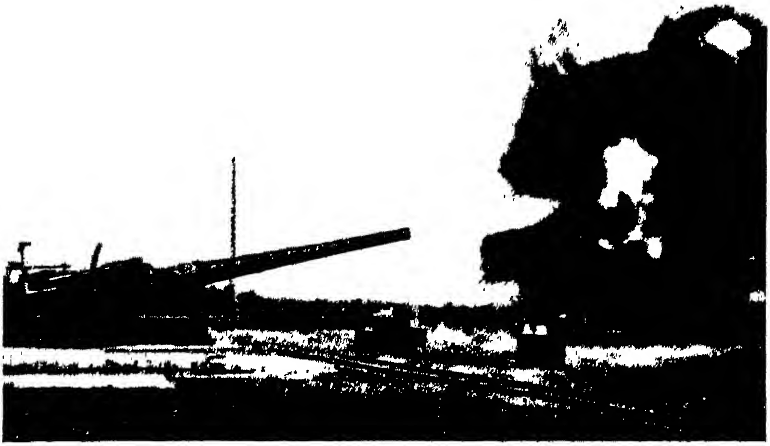


FIG. 57. The discharge of a 16-inch rifle.

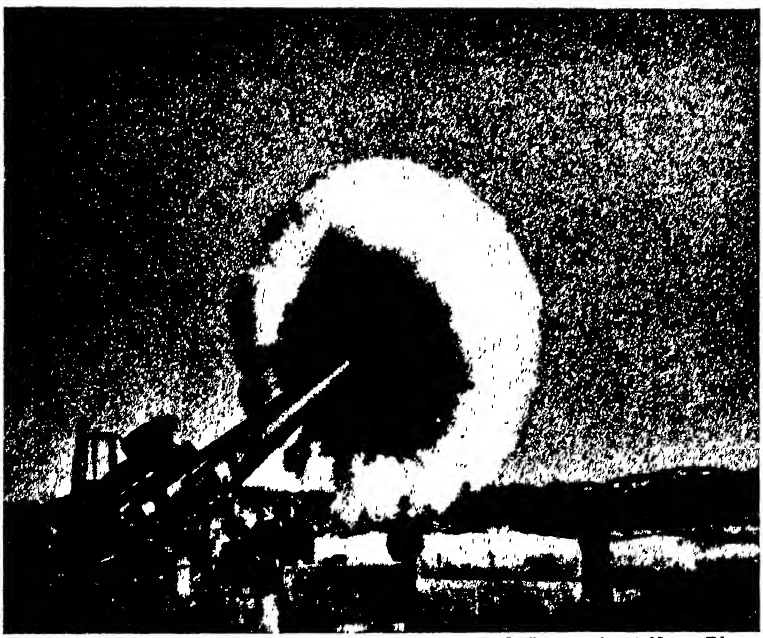


FIG. 58. The discharge of a 16-inch rifle in still air.

rapidly approaches the normal velocity as required by experiment.

The photograph of the discharge of a 16-inch rifle, shown in Fig. 57, illustrates the conditions developed from the mathematical study of the microphone observations. The virtual source of the sound is shot out of the gun and is projected forward with a high velocity which rapidly sub-

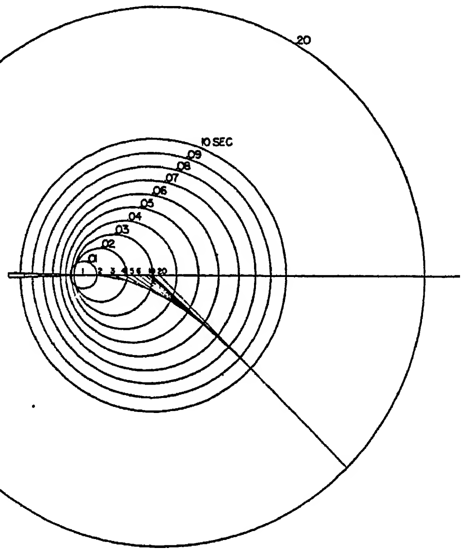


FIG. 59. Propagation of wave fronts of a sound from a large gun.

sides within a hundred feet, more or less, according to the characteristics of the gun. From this point the sound wave develops uniformly with the usual spherical wave-front and with normal speed; this condition is illustrated in Fig. 58. It follows that if the source of the sound is located by observations made at a distance, as by the methods of sound-ranging, the point so determined will be the virtual center in its most advanced position, perhaps a hundred feet in

front of the gun, the point near the center of the smoke cloud in Figs. 57 and 58. The positions of the wave front of the sound from a large gun at successive hundredths of a second to 0.10 second and at 0.20 second are shown in Fig. 59. The radial lines indicate how the apparent source of

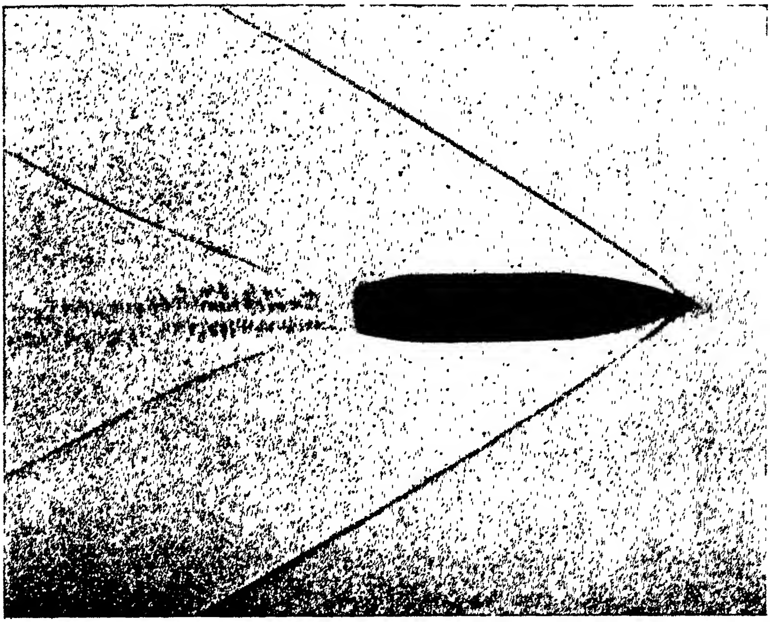


FIG. 60. Sound waves produced by a bullet moving with a velocity of 2700 feet per second.

the sound changes its position with time, becoming fixed in about 0.20 second.

An interesting analogy is given by the nose-wave in air from a bullet moving with a velocity greater than that of sound, Fig. 60. The velocity of the bullet, 2700 feet per second, is about the same as that of the cylinder of compressed gas which is projected from the muzzle of the large

gun. The nose-wave of the bullet is an explosion wave, the high velocity of which is damped exponentially, rapidly approaching the normal speed of sound, these conditions being indicated by the curvature of the wave as it passes the nose of the bullet and becomes straight behind it. The analogy is more evident when the varying velocity of the sound wave from the muzzle of the gun is plotted as in Fig. 61.

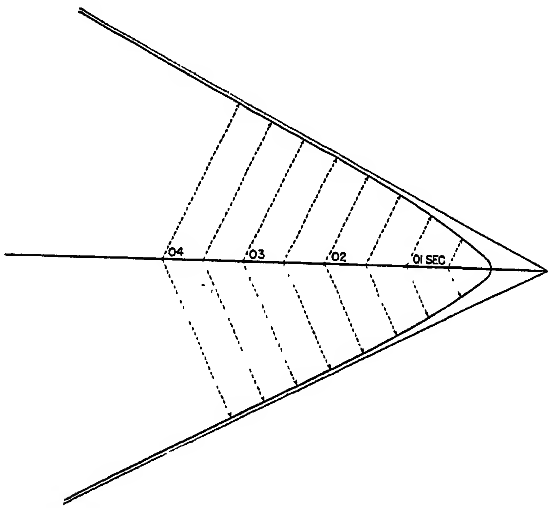


FIG. 61. Wave front of an explosive sound.

The points on the axis marked 0.1 sec, 0.2 sec, etc., are the centers from which the sound started 0.1 second, 0.2 second, etc., before the wave had developed to the extent shown in the chart. These points are located from the known velocity of the projectile. The distances which the sound will have traveled from these centers at the respective time intervals are found from the equation

$$r = Vt + a\,(1 - e^{-bt}).$$

These values of r are used as the radii of circles about the

corresponding points. The smooth-curve envelope of these circles is drawn; this is the heavy-line curve in Fig. 61 which is identical in type with the photograph of the wave in air produced by the bullet in flight shown in Fig. 60.

Some observations of the velocity of the sound, recorded on the phonodeik, were made at the Headquarters Building, located about 1500 feet behind the gun on a line making an angle of 221° with the line of fire. When referred to the muzzle of the gun, the indicated velocity was sub-normal; but when referred to the virtual center as described in the preceding paragraphs, the observed velocity was strictly normal, substantiating the explanations just given.

Experiments on the velocity of sounds from a small cannon were made by W. W. Jacques in 1878, in which he found a sub-normal velocity at stations in the rear of the gun, approaching the normal value as the distance increased.[38] These anomalous phenomena would seem to be explained by the conditions of propagation of the sound here developed.

The adequacy of the formulae and corrections for the propagation of the wave front of the sound from a large gun is shown by the consistency of the observed and calculated positions along the axis as shown in Figs. 54 and 55. It is shown perhaps even more effectively when the formulae are applied to the observations at lateral stations.

Seven sets of observations were made with one microphone in the electric firing-circuit, one attached to the muzzle of the 10-inch rifle, and three microphones located on a line making an angle of 42½° with the line of fire, at distances of about 100 feet, 200 feet and 400 feet from the muzzle of the gun. Five sets of observations were made with six microphones located on a line at an angle of 81°

with the line of fire and at distances of about 100 feet, 200 feet, 300 feet, 450 feet, 600 feet and 1000 feet from the gun. These stations which are within the explosive area of the sound are charted in Fig. 62, and are represented by the dots within circles. Applying the formulae just developed, with all corrections, the locations of the wave front and of its center along the axis, for the time corresponding to the ar-

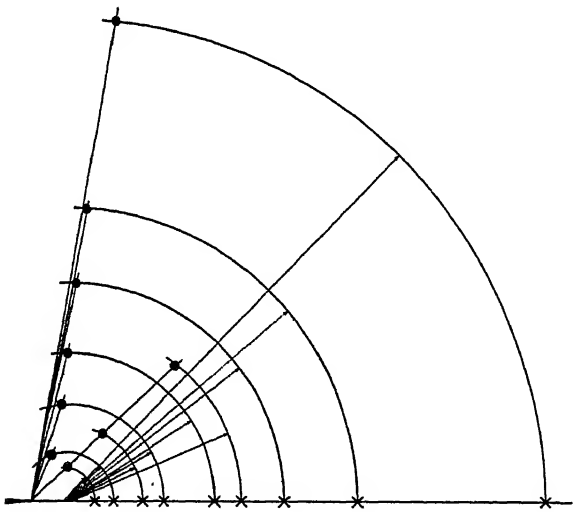


FIG. 62. Comparison of observed and calculated positions of the wave fronts of sounds.

rival of the sound at each of the microphone stations, have been calculated. The positions of the several wave fronts are indicated by the cross marks on the axis. Circles are drawn from the respective centers through the calculated axial points, and these circles intersect the lateral lines almost exactly in the points corresponding to the actual microphone stations. The greatest single deviation of the calculated from the observed wave front is less than 10

centimeters (4 inches), corresponding to a time interval of 0.0003 second.

Under favorable conditions of location and illumination the projectile may be seen in flight. Projectiles of 10-inch, 12-inch, and 14-inch caliber were observed on numerous occasions from Tower A, located just behind the gun emplacements, as they left the muzzle of the gun with a velocity of

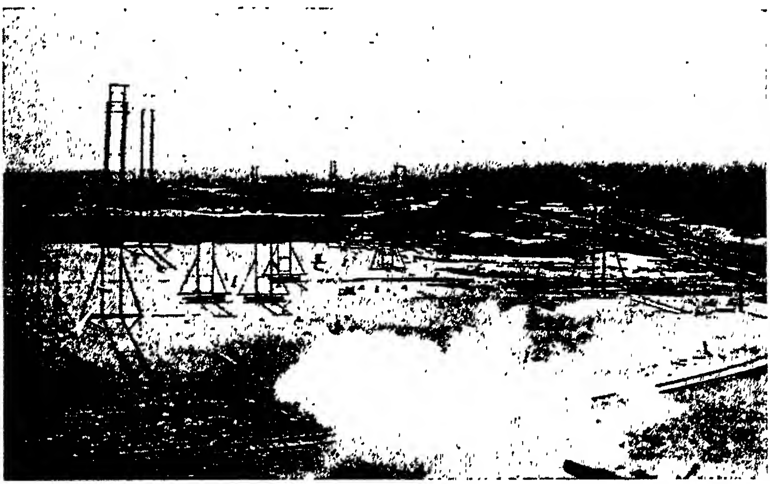


FIG. 63. Terrain over which the velocity of sound was measured, as seen from Tower A.

about 2400 feet per second. The projectile of a 12-inch mortar, having a velocity of 1500 feet per second, was followed by the eye all the way from the muzzle of the gun to the end of the trajectory in the sea. Such a projectile in flight was actually photographed, and is shown near the end of the arrow marked on Fig. 63.

On several occasions the shadow of the sound wave in the air produced by the motion of the projectile itself, was seen very distinctly. This is the kind of wave which is shown in

Fig. 60, produced by the bullet of the 0.30 caliber service rifle; it is analogous to the waves in water produced by the bow of a boat. The wave from the projectile of a 12-inch mortar was observed from Tower A, Fig. 63, the muzzle velocity of the projectile being about 1800 feet per second; the projectile traveled near the ground, the elevation of the gun above horizontal being 1° 17′. The air was clear near the water, but above there was a layer of uniform, thin white clouds, obliterating the glare of the sunlight, yet the position of the sun was visible and there was enough light to cast a very faint shadow. There was a light wind which cleared away the smoke from the gun. The shadow of the sound wave was distinctly seen on the sand, developing from the projectile as it moved over the butts (distance about 500 feet), and to the shore line (distance about 1500 feet), and then the shadow was followed on the surface of the water to the end of the trajectory in the sea at a distance of about 7500 feet. This phenomenon depends upon a rare combination of atmospheric conditions; enough light to cast the shadow of the compression wave, and yet not so much light as to obscure the shadow; a wind to clear away the smoke; and a flat trajectory for the projectile. The observation of similar shadows of sound waves has been reported by C. V. Boys.[39]

CHAPTER IX

THE NORMAL VELOCITY OF SOUND IN FREE AIR

THE VELOCITY OF SOUND OVER LONG RANGES

THE investigations described in the preceding section show that the sound of the discharge of a large gun is propagated at first with an explosive effect, but that this effect is soon dissipated, and that at a distance of a thousand feet from the gun the velocity of the sound differs from the normal velocity in free air by less than one part in a million. This is true of guns as large as those of 10-inch and 12-inch caliber; yet the sounds of such guns can be heard to distances of perhaps ten miles; such sounds are then suitable for precision measurements of the normal velocity of sound.

At Sandy Hook Proving Ground special microphone stations were located on the line of fire of the guns at distances of 100 feet, 300 feet, 1000 feet and 2000 feet from the muzzle of the gun. The regular establishment of the Proving Ground provided two other stations known as Tower B and Tower C, which were located nearly on the line of fire. The microphones in these towers were at distances from the muzzle of the 12-inch gun of 7243.1 feet and 20,312.2 feet respectively. These distances had been accurately surveyed for the regular work of the Proving Ground. Microphones were hung from the rails of the balconies of these towers

about sixty feet above the ground, and were connected by independent circuits with the recording galvanometer in the Headquarters Building. The ground between the guns and these towers was very flat; there were very few trees, and no large buildings or other obstructions of any kind. The line of vision from the guns to these towers was unobstructed. Fig. 63 is the view from Tower A, just behind the gun emplacements, looking towards Towers B and C. During these experiments complete meteorological observations for the velocity and direction of the wind, for the temperature and humidity of the air and for the barometric pressure were made at the Headquarters Building, at Tower B, at Tower C, and at the United States Weather Bureau Station at Sandy Hook.

Eleven sets of records were obtained over this long range which show the progress of the sound pulse from the gun to the distance of 20,312 feet, as recorded at the six stations for each shot. These observations, made on three different days, March 21, 25, and 26, 1919, and with three different types of gun, have been combined in three separate groups; the conditions of gun fire and the meteorological conditions are given in Table IV.

TABLE IV. Meteorological Conditions for Velocity Observations.

Gun	*Velocity of Projectile*	*Max. Gun Pressure*	*Temp.*	*Barometer*	*Humidity*	*Wind Velocity*		*Wind Azimuth*
	ft/sec	lbs/sqin				mi/hr	m/sec	
12-inch Mortar	955	12500	14°.1 c	76.30 cm	52%	19.0	8.5	170°
12-inch Rifle	2688	39500	10.6	76.96	60	8.5	3.8	272
8-inch Rifle	2225	37100	10.1	76.34	75	19.6	8.7	11

The three groups of observations have been reduced by the method of least squares, explained in the preceding sec-

tion, with all corrections applied, to determine the definitive value of V_0, the normal velocity of sound in free air under standard conditions. The results are given in Table V.

TABLE V. Normal Velocity of Sound.

Group I	1087.089 ft/sec	331.344 m/sec
II	.079	.341
III	.212	.382

So far as the conditions of observations are concerned, the three determinations seem to be of equal weight. These investigations lead to the conclusion that the normal velocity of sound in free air under standard conditions at Sandy Hook, measured over a course of 6.19 kilometers (20,312 feet) is

$$331.36 \pm 0.08 \text{ meters per second}$$
$$1087.13 \pm 0.26 \text{ feet per second.}$$

The value for the ratio of the specific heats of dry air at 0°C may be derived from this experimental determination of the velocity of sound. Using Berthelot's equation of state this ratio is 1.4027; using Van der Waals' equation of state the ratio is 1.4031; the mean is

$$\gamma = 1.4029.$$

THE THEORETICAL VELOCITY OF SOUND

What is known as the theoretical velocity of sound in a gas can be derived from a knowledge of the density, elastic constants and specific heats of the gas according to the formula of Newton as modified by Laplace. Dr. Robert S. Shankland has made an extended study to determine the most reliable values of these constants now available and

has calculated the theoretical velocity of sound with the results here given. To the second decimal place, the computed and observed values of the velocity are identical.

The Newton-Laplace formula[40] for the velocity of sound in the air is

$$V = \sqrt{\frac{\gamma p}{d}\phi} \quad ,$$

where V is the velocity of sound, γ is the ratio of the specific heat at constant pressure to the specific heat at constant volume, p is the atmospheric pressure in dynes per square centimeter, d is the density of the air, and ϕ is a correction factor required because the air is not a perfect gas.[41]

The calculation is made for dry air at 0°C, under a pressure of 76 centimeters of mercury, at Sandy Hook Proving Ground, New Jersey. The density of air, presuming the normal content of carbon dioxide for sea air of 3 parts in 10,000 by volume, is $d = 0.0012929$ grams per cubic centimeter.[42] The pressure of the air at the place of observation is $p = 76\delta g$, δ being the density of mercury and g the acceleration of gravity. For this calculation $\delta = 13.5951$ grams per cubic centimeter,[43] and the value of gravity has been especially supplied by the United States Coast and Geodetic Survey for the middle point of the course of the sound in these experiments, having a latitude of 40°26′30″, and at an elevation of 60 feet above sea level: $g = 980.212$.

The ratio of the specific heats of air, γ, has been directly determined by various experimenters by observing the temperature and pressure changes resulting from the adiabatic expansion of air and by Johnston from a spectroscopic study of the properties of ideal gases. Among these determinations, reference is made to those by the following investiga-

tors,[44] the results of each, reduced to standard conditions, being given in parentheses: Lummer and Pringsheim (1.4025), Shields (1.4029), Partington and Howe (1.4034), Brinkworth (1.4032), and Johnston (1.4025). The mean of these five determinations is adopted for the present purpose, giving for the value of the ratio of the specific heats of dry air at 0°C, under a pressure of 76 centimeters of mercury, $\gamma = 1.4029$.

The correction factor ϕ, according to Berthelot's equation of state, is

$$\phi = 1 + \frac{9}{64} \cdot \frac{p}{p_c} \cdot \frac{T_c}{T} \left(1 - 6 \frac{T_c^2}{T^2}\right),$$

where p is the pressure in dynes per square centimeter, and p_c is the critical pressure (37.68×10^6 dynes per square centimeter); T is the absolute temperature and T_c is the critical temperature of air (132.3 K). For the conditions $p = 76$ centimeters of mercury and $T = 0°C$, $\phi = 0.999251$. If Van der Waals' equation of state is adopted, the correction factor is

$$\phi = 1 + \frac{1}{4} \cdot \frac{p}{p_c} \frac{T_c}{T} \left(1 - \frac{27}{8} \cdot \frac{T_c}{T}\right),$$

which gives for standard conditions, $\phi = 0.998930$. Using the values thus derived for the several constants for air, the calculated velocity of sound in free air at 0°C, under standard conditions at Sandy Hook Proving Ground, using Berthelot's equation of state, is 331.384 meters per second; using Van der Waals' equation of state the calculated velocity is 331.331 meters per second. The theoretical velocity of sound, adopting the mean, is

$$V_0 = 331.36 \pm 0.05 \text{ meters per second.}$$

Various Determinations of the Velocity of Sound

The earliest attempt to determine the velocity of sound by experimental methods was made about 1640 by Mersenne, while the first direct measurements were made under the auspices of the *Accademia del Cimento* of Florence in 1656 by Borelli and Viviani. From this time to the present, there have been many determinations of the velocity of sound by various methods and under widely varying conditions. An historical résumé of these experiments is given in the author's "Anecdotal History of the Science of Sound," while more extended accounts of the important researches may be found in the works of Auerbach, Trendelenburg, Rowland, Violle, and Barton, cited in the references.[45] Extended bibliographies are given by A. L. Foley in the "International Critical Tables" and also in "Landolt und Börnstein's Physikalisch-Chemische Tabellen."[46]

Three different methods of measurement have been used in recent determinations; one depends upon the measurement of the time required for the sound to traverse a known distance in the open air; a second method determines the wave length of a high-frequency sound, the experiments being made in a laboratory room; in the third method the measurements of one or the other of the two types mentioned are made in air contained in larger or smaller tubes, the direct results being corrected by empirical formulae to give the velocity in free air. Since 1908, several determinations of the velocity of sound have been made with high precision by each of these methods, of which the following are of interest in relation to the results here reported.

Determinations by the first method, the sound progressing in the open air over long ranges, have been made by Esclan-

gon,[47] by Angerer and Ladenburg,[48] and by Miller, each taking advantage of facilities provided by the War Departments of France, Germany, and the United States of America, respectively. Esclangon's observations, made in 1917 and 1918, used guns of calibers ranging from 14 centimeters to 52 centimeters and ranges from 1.4 kilometers to 14 kilometers. The experiments of Angerer and Ladenburg, made in 1916–1918, used an elaborate system of ranges extending to distances of 11 kilometers, the source being high-explosive powder. Miller, in 1919, used guns of 20 centimeters and 30.5 centimeters caliber, over a range of 6.19 kilometers. The velocities obtained are:

Esclangon	330.9 m/sec
Angerer and Ladenburg	330.8
Miller	331.36

Determinations of the velocity by the second method, the measurement of the wave length of the sound from a high-frequency source made in a laboratory room, give the following results: [49]

Hebb	331.41 m/sec
Pierce, Reid and Grabau	331.68

Determinations by the third method, the measurements being made in tubes of about five centimeters diameter, the values reported being reduced to the condition of free air, are as follows: [50]

Thiessen	331.92 m/sec
Grüneisen and Merkel	331.57
Partington and Shilling	331.4

There are some evidences of systematic differences between the results obtained by the different methods. The velocity determined over long ranges is less than when measured in a laboratory room, and the velocity derived from

measurements in tubes is the highest. However, the actual speed of the sound in tubes is always lower than the value reported for the velocity in free air, and the latter may be too great because of the use of imperfect empirical formulae for the correction from tube to free air.

The three determinations over the long ranges all used a similar procedure and had unusually complete facilities for the experiments. The mean of the observations of Esclangon and of Angerer and Ladenburg gives a velocity of 330.85 meters per second over a mean range of 12.5 kilometers, while the observations of Miller show a velocity of 331.36 meters per second over a range of 6.2 kilometers. This difference would seem to be greater than the uncertainties of observation and correction of measures, and it may be due to a real reduction in the speed with increasing distance from the source. The lessening of speed with increasing distance from the source has been definitely shown in the experiments with high-frequency and short-wave sounds as reported by Hebb (1905); and by Pierce and Reid. Is it possible that the velocity of light may also change over great distances?

The experimental evidence regarding a possible change of type for waves traversing long distances is not sufficient to determine the effect upon the speed of the wave. Two phonodeik records of the sound from the fog horn located at Father Point, Quebec, are shown in Fig. 64; the upper curve is the wave form recorded near the station, while the lower curve is the record of the same sound photographed at a distance of 2 miles (3.2 kilometers) over the water of the St. Lawrence River; both records were taken on the axis of the horn.[17]

At the International Congress of Physics, Paris, 1900,

Violle gave a report on the velocity of sound in which he reviewed all of the determinations which had been made previous to that time, and reported as the most probable value the velocity of 331.36 meters per second under standard conditions.[51] The average of the seven values obtained since 1908 by three different methods as given in the above

FIG. 64. Phonodeik records of a fog horn, near-by and at a distance of two miles.

references, is 331.38 meters per second. The theoretical value for the velocity of sound, computed by Dr. Shankland according to the Newton-Laplace formula as given in the preceding section, is 331.36 meters per second. The direct experimental determination of the velocity of sound in free air here reported gives the value 331.36 meters per second.

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